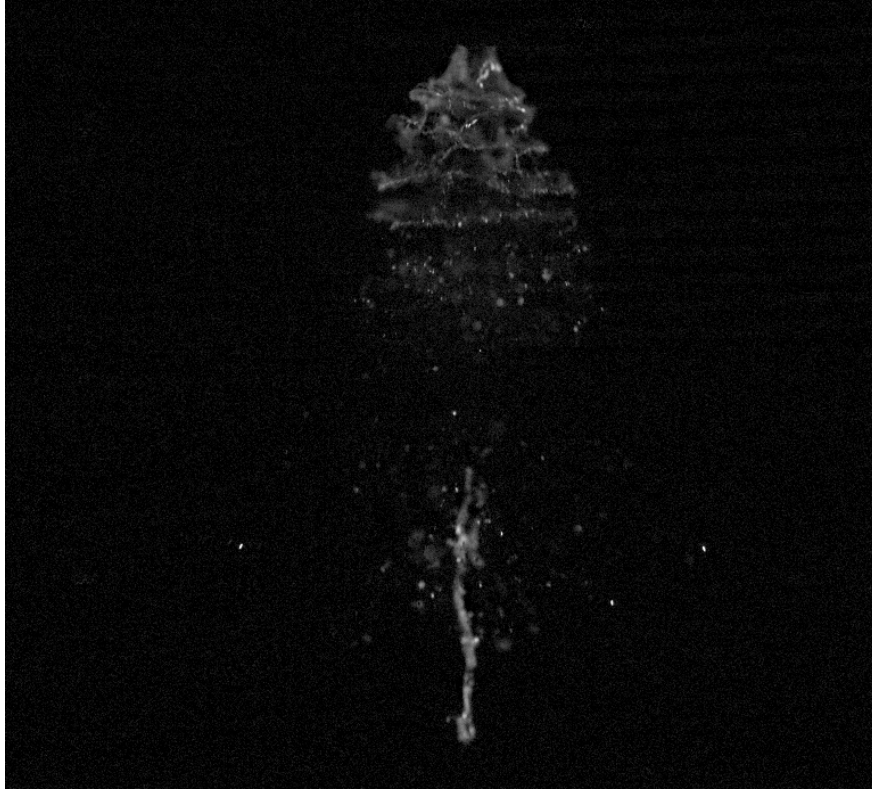




**CHALMERS**  
UNIVERSITY OF TECHNOLOGY



# Urea Injection Pattern Characterization for SCR Systems

Experimental Determination of Key Spray Properties

Master's thesis in Sustainable Energy Systems

AXEL THORÉN

DEPARTMENT OF CHEMISTRY AND CHEMICAL ENGINEERING

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CHALMERS UNIVERSITY OF TECHNOLOGY  
Gothenburg, Sweden 2026  
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MASTER'S THESIS 2026

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*Division of Chemical Engineering*  
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AXEL THORÉN

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Cover: Opening of a pressure-driven swirl injector.

Typeset in L<sup>A</sup>T<sub>E</sub>X  
Printed by Chalmers Reproservice  
Gothenburg, Sweden 2026

## Abstract

This thesis presents an experimental characterization of urea-water solution injection for selective catalytic reduction systems, focusing on key spray properties of two injectors relevant to Volvo Penta applications. The work was motivated by the need to improve urea evaporation, mixing, and nitrogen oxide (NO<sub>x</sub>) reduction performance while reducing the risks of wall impingement, crystallization, and ammonia slip. The aim was to improve understanding of a new supplier injector by comparing it with a currently used injector and, at the same time, establish practical in-house optical measurement capability for future injector evaluation. Due to project limitations, the study was restricted to spray characterization upstream of the selective catalytic reduction (SCR) under simplified conditions in quiescent air.

A dedicated test rig was developed using high-speed imaging with back-light imaging, planar laser imaging, and microscopic back-light imaging. Together with Python-based image processing, the setup was used to determine spray cone angle, penetration length, droplet size distribution, spatial droplet distribution, and droplet velocity for a comparative evaluation of the two injectors. Experiments were conducted at a fixed injection pressure of 900 kPa using 32.5 wt% urea-water solution. The effects of mass-flow rate, axial and radial measurement position, injection temperature, and injector type were investigated.

The results show that injector geometry had a clear influence on both macroscopic and microscopic spray behaviour. The swirl injector produced a wider spray cone and a more hollow-cone structure, while the six-hole injector produced a narrower cone and faster initial penetration growth. Mass-flow rate had little effect on spray cone angle and penetration length for either injector, but the droplet size distribution of the swirl injector changed with mass-flow, with lower mean diameters observed at higher flow rates. Spatial position strongly affected the measured droplet population: more droplets and smaller droplet sizes were found farther from the spray centreline and downstream, consistent with the hollow nature of the swirl spray and continued spray development. Elevated injection temperature to 40 °C caused only limited changes in droplet size and no clear change in droplet velocity. Compared with the swirl injector, the six-hole injector generally produced larger droplets. Overall, the study demonstrates that relatively simple optical methods can provide useful in-house spray characterization data for injector comparison, further development, and computational fluid dynamics (CFD) model validation.

Keywords: spray, urea, droplets, SCR, back-light imaging, planar laser imaging, spray cone angle, penetration length, droplet size distribution, droplet velocity



## Acknowledgements

First, I want to express my gratitude to the whole Exhaust After-Treatment System group at Volvo Penta for giving me the opportunity to conduct my master's thesis at Volvo Penta. It was a rewarding and enjoyable experience where everyone made me feel very welcome from day one. I would especially like to thank my two supervisors, Masoud Salehi and Mahyar Saffari, at Volvo Penta for their guidance and motivating attitude that made this project even more enjoyable. Finally, I thank my examiner, Derek Creaser, for his input and comments on the report.

Axel Thorén, Gothenburg, May 2026

# Abbreviations

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Below is a list of the most important abbreviations used throughout this thesis, presented in alphabetical order. Each term is written out in full and formatted in *italics* when it first appears in the text. Lowercase abbreviations are used for units.

|                 |                                |
|-----------------|--------------------------------|
| ACM             | After-treatment control module |
| BLI             | Back-light imaging             |
| CFD             | Computational fluid dynamics   |
| fps             | Frames per second              |
| LDA             | Laser Doppler anemometry       |
| LED             | Light-emitting diode           |
| MBLI            | Microscopic back-light imaging |
| NO <sub>x</sub> | Nitrogen oxides                |
| PLI             | Planar laser imaging           |
| RT              | Room temperature               |
| SCR             | Selective catalytic reduction  |
| SOI             | Start of injection             |
| SMD             | Sauter mean diameter           |
| UWS             | Urea-water solution            |

# Nomenclature

---

Below is the nomenclature of the indices and variables that have been used throughout this thesis.

## Indices

|      |        |
|------|--------|
| $px$ | Pixels |
| $r$  | Radial |
| $z$  | Axial  |

## Variables

|                       |                                                                       |
|-----------------------|-----------------------------------------------------------------------|
| $A$                   | Area                                                                  |
| $C$                   | Circularity                                                           |
| $d$                   | Droplet diameter                                                      |
| $d_x$                 | Droplet diameter below which $x\%$ of droplets lie, on a number basis |
| $\bar{d}$             | Arithmetic mean droplet diameter                                      |
| $e$                   | Eccentricity                                                          |
| $Eo$                  | Eötvös number                                                         |
| $L$                   | Characteristic length                                                 |
| $L_p$                 | Penetration length                                                    |
| $L_{px}$              | Physical pixel length                                                 |
| $mpp$                 | Metres per pixel                                                      |
| $N_{\text{droplets}}$ | Number of detected droplets                                           |
| $N_{\text{images}}$   | Number of images                                                      |
| $P$                   | Perimeter                                                             |

---

|                       |                                |
|-----------------------|--------------------------------|
| $\phi_c$              | Spray cone angle               |
| $\rho_f$              | Density of surrounding fluid   |
| $\rho_{\text{UWS}}$   | Density of urea-water-solution |
| $\sigma$              | Standard deviation             |
| $\sigma_s$            | Surface tension                |
| $t$                   | Welch's t-test statistic       |
| $t_{\text{exposure}}$ | Exposure time                  |
| $u$                   | Velocity                       |
| $u_r$                 | Radial velocity                |
| $u_{\text{rel}}$      | Relative velocity              |
| $u_z$                 | Axial velocity                 |
| $V$                   | Volume                         |
| We                    | Weber number                   |

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# 1

## Introduction

---

In 2024, the transportation sector accounted for approximately 30% of the global energy consumption [1], with the main fuels being of fossil origin such as gasoline and diesel. Of this 30%, road transport makes up the biggest part. Shipping makes up less than 10% of the transport energy consumption globally, whereas it is slightly higher in the EU at around 12% [2]. Although a transition from fossil fuels to renewable energy carriers is beneficial because it reduces dependence on finite resources, it does not in itself eliminate combustion-related emissions such as nitrogen oxides, NO<sub>x</sub>, carbon monoxide, CO, and unburnt hydrocarbons, HC, since these are strongly linked to the combustion process itself. An efficient exhaust after-treatment system is therefore crucial for environmental and legal reasons, independent of the nature of the fuel for these engines.

NO<sub>x</sub> is one of the most harmful emissions among those mentioned above and can lead to respiratory damage, smog formation, and acid rain [3]. Most commonly, the NO<sub>x</sub> after-treatment system consists of injecting a spray of *urea-in-water solution* (UWS) into a *selective catalytic reduction* (SCR) system [4], where a schematic is shown in Figure 1.1 illustrating the NO<sub>x</sub> conversion.

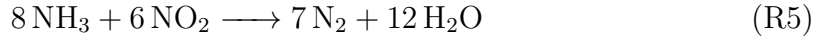
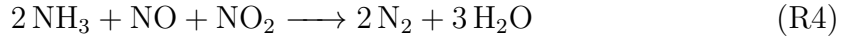
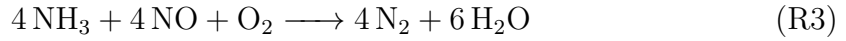


**Figure 1.1:** Simple schematic illustrating the principle of an SCR unit.

Using a spray combines mass and heat transfer, leading to an effective vaporization process. Urea,  $CO(NH_2)_2$ , is used instead of pure ammonia since it is much less toxic and is thus easier to store and handle. It decomposes to form ammonia,  $NH_3$ , through the reactions



which then reacts with the NO<sub>x</sub> to form inert nitrogen gas, N<sub>2</sub>, in the following reactions.



SCR is today a well-established technique, but nevertheless challenges remain, and it is desired to achieve as high conversion and efficiency as possible. For this, proper injection and mixing of UWS is important to obtain a rapid vaporization of droplets. This is governed by key parameters such as droplet size, velocity, spatial distribution, spray cone angle, and penetration length [5]. Poor distribution of the injected UWS can cause several issues, one of which is that ammonia can pass through the SCR without reacting. This is referred to as ammonia slip [6] and its level is, like NO<sub>x</sub> emissions, restricted by laws. Another issue is that UWS droplets can impinge on the exhaust pipe surface, causing crystallization [7], which leads to lower conversion rates.

The injection process is, in turn, influenced by the exhaust environment, such as varying pressures, temperatures, and flow velocities. This affects spray patterns, droplet evaporation, and subsequent chemical reactions, thus influencing the NO<sub>x</sub> reduction efficiency. Previous studies have examined nozzle design and fluid properties. However, there is a growing need to understand how real-world exhaust conditions affect the behaviour of urea injection. Although such conditions are important, the present study is limited to quiescent air and focuses on injector spray characterization under simplified conditions. This study was conducted at Volvo Penta with both currently existing setups as well as tailored setups for this project.

## 1.1 Aim and Objectives

The aim of the project was to improve the understanding of an injector from a new supplier to Volvo Penta and compare it to a currently used injector by implementing common optical measurement techniques in-house for future use.

## 1.2 Scope and Purpose

Several limitations were set before the project, mainly that no interaction with real exhaust could be studied, making the scope limited to characterizing the dispersion of the UWS droplets from the spray upstream of the SCR through experimental work. That is, no NO<sub>x</sub> conversion was examined. Furthermore, no actual exhaust gas could be treated, and quiescent air was used instead. The spray parameters of interest were droplet size distribution, spatial distribution, mean velocity, spray

cone angle, and penetration depth. Measuring techniques were limited to a high-speed camera with back-light. This technique was chosen since most of the needed equipment already existed at Volvo Penta.

The purpose of the project was to characterize the spray parameters mentioned above with available optical measuring techniques. Another objective was to construct a new test rig involving these measuring techniques. Based on the results, conclusions were drawn regarding how injector type, mass-flow, measurement position, and limited temperature variation affected the observed spray characteristics under simplified conditions. The results can also be used as initial and boundary conditions for future numerical simulations which are currently lacking.

# 2

## Theory

---

This chapter covers relevant theory from the literature that underpins the methodology and the interpretation of the results. First, urea and its crystallization are briefly discussed. Then, the focus shifts to describing the physics of a spray, the characterizing parameters of a spray, and relevant measuring techniques that were used in the experimental part of the project. In this thesis, spray refers to what comes out of the injector, i.e. the ensemble of UWS droplets. The injector is defined as the hardware producing the spray.

### 2.1 Urea

As mentioned in the introduction, the use of urea in SCR systems is a well-established method for converting  $\text{NO}_x$  into  $\text{N}_2$ . The dynamic viscosity of urea is approximately 40% higher than water at room temperature [8], which affects the spray physics. Compared to water, urea does not have a conventional boiling point since it starts to decompose into  $\text{NH}_3$  approximately 135 °C. For most applications, AdBlue is used as UWS which has approximately 32.5 wt% urea [9].

Crystallization of urea is a well-known problem for SCR applications, caused by a combination of several factors [10] where evaporation of water from the UWS is central [10], [11]. These factors can be divided into two categories: operating condition factors such as exhaust temperature and structural factors such as injector design [10]. During the process of crystallization the urea reacts with isocyanic acid,  $\text{HNCO}$ , formed in reaction R1, which produces biuret in the following reaction [12].



The biuret produced in reaction R6 can react further into larger complexes, causing deposits of crystals. These deposits often form at the injector outlet and exhaust downstream parts, causing several adverse effects on the system. The formed crystals cause a decrease in cross-sectional area, thus increasing the back-pressure [10], [13]. It also means that not all urea is ultimately converted into ammonia, which leads to worsened  $\text{NO}_x$  conversion. Furthermore, if the crystallization occurs at the injector outlet, the spray properties will be affected.

The spray characteristics, described in a later section, also have a significant impact

on the crystallization [10]. These affect the dispersion and evaporation rate of the urea which are important factors affecting the process. Although crystal formation is not the main focus of this report, it is an important aspect to consider.

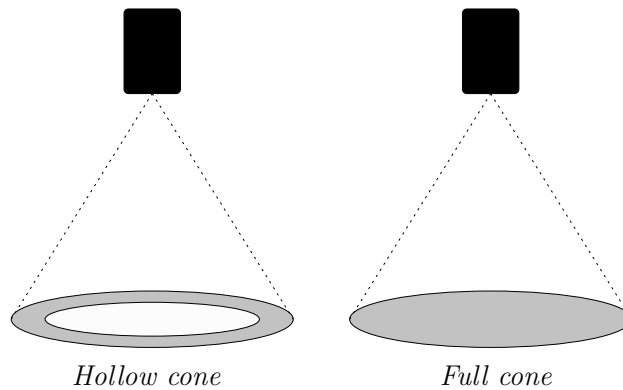
## 2.2 Spray Physics

In essence, a spray is generated when there is a sufficiently high relative velocity between the injected liquid and the surrounding gas [14]. The purpose of using a spray in an SCR system is to disperse the liquid into droplets, thereby accelerating evaporation and promoting efficient coupled heat and mass transfer, improved mixing, and conditions favourable for chemical conversion.

### 2.2.1 Injector Types

Injectors can be designed in a multitude of ways and this is expected to affect the shape of the spray [14]. In general, the internal geometry of pressure-driven injectors consists of a passage or a tube followed by an abrupt contraction into a much smaller orifice with a certain length [5]. This abrupt change causes a rapid pressure drop and kinetic energy of the fluid flow is utilized to break it up into droplets.

Hydraulic injectors, that is, pressure-driven injectors, are among the most common injector types, in contrast to air-assisted injectors [15], [16]. There is a wide range of pressure-driven injectors and a single injector can fall into several categories simultaneously [14]. Some examples include single-hole injector, multi-hole injector, and swirl injector. Depending on the type of pressure-driven injector, the spray cone can be either a so-called hollow or full cone, as illustrated by Figure 2.1. In a full-cone spray, the droplets are distributed more uniformly across the spray cross-section, whereas in a hollow-cone spray the droplets are concentrated more toward the outer edge.



**Figure 2.1:** *Illustration of hollow and full cone sprays.*

In a swirl injector, the injected fluid is subjected to centrifugal forces inside the injector, forming a liquid sheet that subsequently breaks up into droplets [17]. Swirl injectors can also be designed to produce either hollow- or solid cone, although hollow

cone sprays is more common. Information about the injectors that were studied in this project is presented in Table 2.1. One major difference between them, apart from injector #1 being a swirl injector, is that injector #1 has a circular slit instead of six discrete holes.

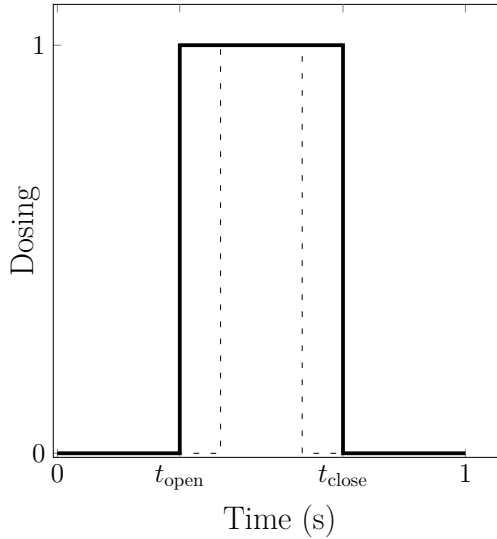
**Table 2.1:** *Specifications for the injectors that were studied in the project.*

| Injector | Type                                     | Mass-flow (g/s) |
|----------|------------------------------------------|-----------------|
| #1       | Pressure-driven swirl, one circular slit | 0.2-3.3         |
| #2       | Pressure-driven, six holes               | 0.2-3.3         |

### 2.2.2 Dosing

Figure 2.2 illustrates the injector signal used for UWS dosing. It shows the periods during which dosing occurs within one second, where 1 indicates that dosing is active and 0 indicates that no dosing takes place. The width of the signal, that is, the dosing duration, is controlled by the mass-flow rate. Increasing the mass-flow widens the signal, and decreasing it narrows the signal. Setting the mass-flow rate to its maximum results in a near continuous injection.

In practice, the delivered injection rate does not follow the control signal instantaneously, but instead usually transitions more smoothly. As a result, the time intervals indicated with filled lines in Figure 2.2 do not have full dosing before reaching its quasi-steady state. This area also indicates the opening and closing of the injector, and therefore the early development and the decay of the spray, referred to here as the transient states.

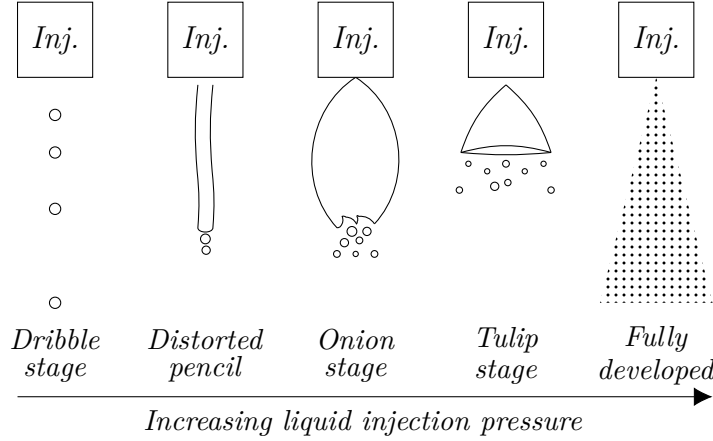


**Figure 2.2:** *Example of a 1 Hz signal to the injector for the dosing with transient state in the filled area. The proportion of the transient states has been increased for visibility.*



### 2.2.3 Droplet Breakup and Morphology

The process of breakup of the bulk fluid in the injector into droplets occurs through atomization which refers to conversion into readily evaporating droplets. Spray development intensifies as the relative velocity between the fluid and surrounding gas increases which in a pressure-driven injector is controlled by the injection pressure. Lefebvre and McDonell [17] describe the spray development with increasing liquid injection pressure throughout the five regimes presented in Figure 2.3. In this report, the stages prior to the fully developed spray will be denoted the transient phase.



**Figure 2.3:** Illustration of spray development with increasing liquid injection pressure. Adapted from [17].

Although the governing physics of atomization is complex, the fully developed stage is usually described as evolving through two main stages: primary breakup and secondary breakup, although the transition between these stages is not always sharply defined. Primary breakup comprises the initial disintegration of the liquid exiting the nozzle into ligaments and larger droplets. This is largely driven by cavitation and turbulence [5], [15]. Cavitation denotes the formation of vapour cavities in the fluid flow when the local pressure drops below the liquid vapour pressure and is affected by the injection geometry and pressure.

Secondary breakup, which is mainly driven by aerodynamic forces, refers to the subsequent disintegration of droplets [15]. A standard measure of the tendency for droplet breakup is the Weber number,

$$\text{We} = \frac{\rho_f u_{\text{rel}}^2 L}{\sigma_s} \quad (2.1)$$

where  $\rho_f$  is the density of the surrounding fluid to the droplet,  $u_{\text{rel}}$  is the relative velocity between droplet and surrounding fluid,  $L$  is the characteristic length, and  $\sigma_s$  is the surface tension coefficient. The Weber number represents a ratio between aerodynamic inertial and surface tension forces. A larger Weber number indicates that aerodynamic forces are stronger relative to surface tension, which increases the likelihood of droplet breakup. This is typically the case for larger droplets, since the characteristic length, here taken as the droplet diameter, is larger.

To assess the influence of gravity-induced deformation relative to surface tension, the Eötvös number, sometimes also called the Bond number [18], is often used,

$$\text{Eo} = \frac{\Delta\rho g L^2}{\sigma_s} \quad (2.2)$$

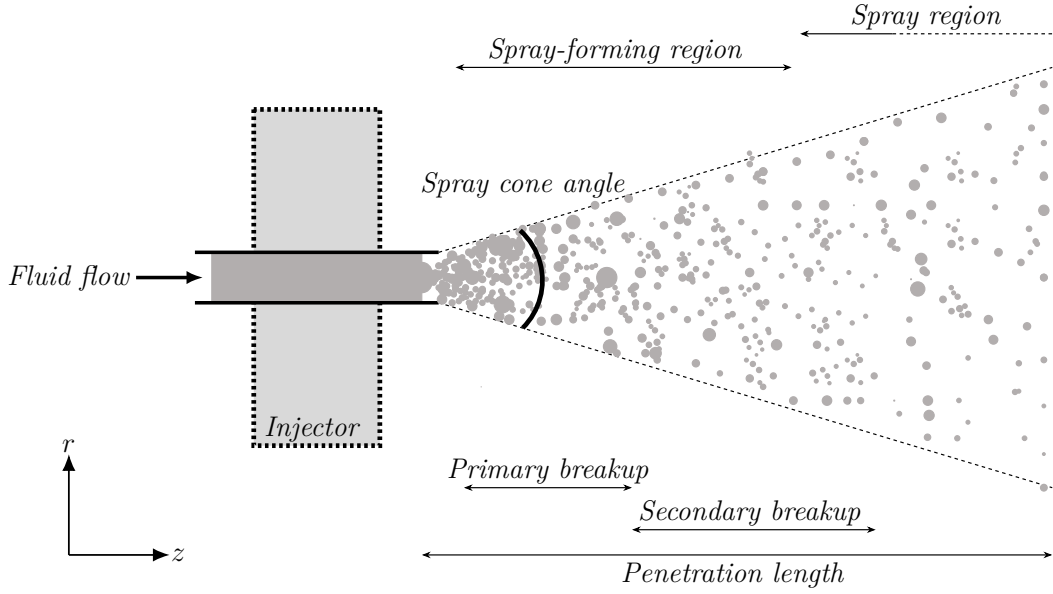
where  $\Delta\rho$  is the density difference between droplets and surrounding fluid and  $g$  is gravitational acceleration. The ratio can be interpreted as a comparison of buoyant and surface tension forces and indicates whether a droplet stays spherical under gravity. When  $\text{Eo} \ll 1$ , surface tension forces dominate over buoyancy, and droplets are expected to be nearly spherical. In sprays, the buoyant force is generally small because air has a low density compared to the injected liquid. In addition, for very small droplets, the characteristic length is small, which makes the Eötvös number low. Therefore, droplets with small diameters can generally be expected to remain nearly spherical.

## 2.3 Spray Characteristics

Two basic classes of spray characteristics can be identified: macroscopic and microscopic [19]. Macroscopic characteristics include spray penetration length, spray cone angle, and the derivatives of them. Microscopic characteristics include droplet size distribution, droplet velocity, and droplet spatial distribution. These are more experimentally demanding to measure compared to the macroscopic characteristics due to the difference in scales.

### 2.3.1 Macroscopic Properties

Figure 2.4 depicts a conceptual fully developed spray including the macroscopic properties of interest [5]. The spray cone angle,  $\phi_c$ , is in this thesis defined as the angle formed between two external fitted lines from the nozzle 25 mm downstream, since the spray is usually most defined around there [20]. Another reason is that the obtained data is aimed to be used for simulations, where the flow downstream should be calculated. This parameter describes the average spreading of the UWS and is thus connected to the spray width, which is defined as the distance of the widest section of the spray pattern margins. In a similar manner the penetration length,  $L_p$ , can be defined as the length between the furthest downstream location of the coherent spray from the nozzle exit of the injector. Knowledge about this parameter is specifically important to avoid wall impingement [21] and possible subsequent crystallization.



**Figure 2.4:** Macroscopic spray properties of a conceptual spray illustrating the radial and axial distribution of droplets. Adapted from [5].

A common approach in engineering is to divide the spray into two regions, often denoted the dense region and dilute region [5]. The dense region is the closest region to the injector where the droplets are more like a dense cloud, whereas the dilute region consists of more dispersed and more clearly distinguishable individual droplets. Relative to the dilute region, droplets in the dense region are generally expected to be larger and exhibit greater size variation. However, the dense region can be optically dilute and vice versa. Thus, the terms spray-forming region and spray region, as used by Kristensson et al [5], are adopted here.

In the literature there are various ways of defining the macroscopic properties mentioned above, as well as several methods of obtaining them [22]. For example, the distance over which a linear fit should be applied to determine the spray cone angle is somewhat ambiguous, and in some cases no linear fit is used at all. Definitions of where the dilute region ends is also somewhat inconsistent. Comparison of results between different studies can therefore be challenging.

## 2.3.2 Microscopic Properties

### Droplet Size

Spray systems can generally be described as a polydisperse and inhomogeneous ensemble of droplets [5], and most practical injectors give droplets in the size range of a few  $\mu\text{m}$  to around  $500\text{ }\mu\text{m}$  [14]. However, no current general theory exists for predicting the size distribution, and experimental methods are therefore necessary to determine the size variations. Once raw data from experiments have been obtained, the distribution of average droplet size can be described in various ways. One common metric for size description of particles and droplets is using the so-called *Sauter mean diameter* (SMD) [15]. The SMD is defined as the diameter of a droplet

whose volume-to-surface-area ratio is the same as that for the entire ensemble of droplets. It can be expressed as

$$SMD = d_{32} = \frac{\sum_{i=1}^N d_i^3}{\sum_{i=1}^N d_i^2} \quad (2.3)$$

which comes from equating

$$\left(\frac{V}{A}\right)_{\text{droplet}} = \frac{(\pi/6)SMD^3}{\pi SMD^2} = \frac{SMD}{6} \quad (2.4)$$

and

$$\left(\frac{V}{A}\right)_{\text{spray}} = \frac{\sum_{i=1}^N d_i^3}{6 \sum_{i=1}^N d_i^2}. \quad (2.5)$$

The SMD is particularly useful for many physical processes. One example being evaporation of spray droplets, since it is heavily dependent on the surface area per volume. In fact, it was first used for studying droplet formation in sprays [23]. A small SMD means a lower volume per surface area, indicating a more effective evaporation. However, the SMD does not explain the actual distribution of droplet sizes. A convenient way to present the distribution is to calculate the equivalent diameter for each droplet in the population since the shape will be almost spherical as explained previously. A histogram, or a frequency distribution plot, can then be plotted with an arithmetic mean diameter of

$$\bar{d} = \frac{1}{N} \sum_{i=1}^N d_i \quad (2.6)$$

and Figure 2.5 depicts a simplified typical frequency-based histogram of droplet diameter. Commonly Weibull,

$$f(d; \lambda, k) = \frac{k}{\lambda} \left(\frac{d}{\lambda}\right)^{k-1} \exp \left[ - \left(\frac{d}{\lambda}\right)^k \right], \quad (2.7)$$

log-normal,

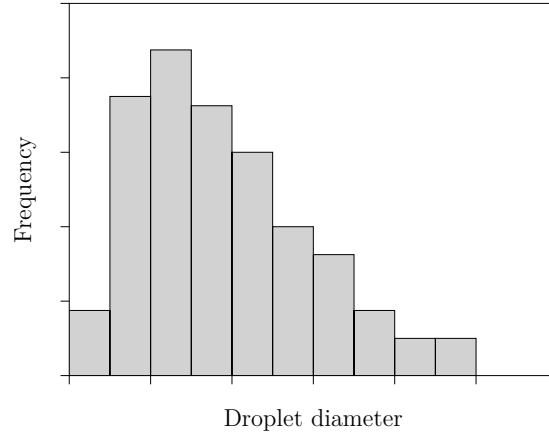
$$f(d; \mu, \sigma) = \frac{1}{d\sigma\sqrt{2\pi}} \exp \left( - \frac{(\ln d - \mu)^2}{2\sigma^2} \right), \quad (2.8)$$

and gamma,

$$f(d; \alpha, \theta) = \frac{1}{\Gamma(\alpha)\theta^\alpha} d^{\alpha-1} \exp \left( - \frac{d}{\theta} \right), \quad (2.9)$$

distributions can describe spray droplet sizes well [24], [25]. In such a histogram, further ways to describe the size distribution can be to include the diameter where a certain percentage of droplets lie below [23]. For example,  $d_{10}$ ,  $d_{50}$ , and  $d_{90}$  express

the diameter below which 10% / 50% / 90% of the droplets lie, respectively. It follows directly that the order of size will always be so that  $d_{10} < d_{50} < d_{90}$ . Less intuitive might be where the SMD is expected to be. Commonly it falls between  $d_{50}$  and  $d_{90}$ , but not necessarily depending on the distribution shape.



**Figure 2.5:** *Typical histogram for droplet size based on frequency.*

### Droplet Spatial Distribution

In addition to the droplet size, it is also important to understand the spatial distribution of droplets, including local number density and segregation. One reason is to understand whether coalescence, that is, the merging of droplets, occurs since this can lead to poorer vaporization. For some swirl injectors, it has been observed that smaller droplets are more prevalent toward the spray centreline and larger toward the cone periphery [17]. The spatial distribution also varies with axial distance from the injector, as more defined separation will occur further away from the injector which is related to the previously explained dense- and dilute spray regions.

The spatial distribution is also important when deciding where sampling should be performed in order to obtain a representation of the droplet size distribution that is as accurate as possible. If the mean diameter varies substantially across different locations in the spray, then the measurements from only one or a few positions may not be representative of the full droplet population. In previous studies [26], [27] it has been common to evaluate the size at both different axial and radial positions.

### Velocity

Droplet velocity depends on injector type, fluid properties, and the pressure applied to the fluid [28]. Close to the nozzle the droplet velocity is primarily governed by the injector conditions, whereas farther downstream it becomes increasingly influenced by aerodynamic drag and may approach a quasi-homogeneous value. This velocity is then strongly related to the droplet size and shape. Larger droplets retain their momentum for longer and are therefore less

susceptible to deflection by the surrounding flow [15]. Smaller droplets, in contrast, are more strongly affected by aerodynamic drag.

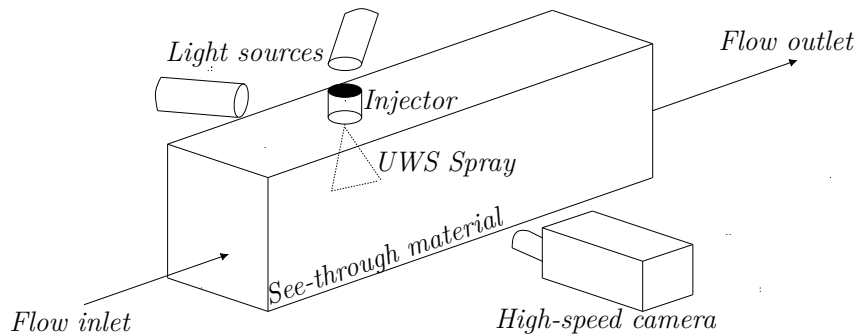
Previous studies on sprays report varying intervals of droplet velocities. Most commonly, the order of magnitude is expected to be  $10^0$  to  $10^1$  m/s [29], [30], with variations depending on average droplet size and injector system. The value can also vary depending on what velocity type is reported, e.g. axial, radial, or magnitude. Measurement technique is also expected to affect the value. Image-based measurement techniques generally provide only projected or in-plane velocity information, whereas the true droplet motion is three-dimensional.

## 2.4 Optical Measurement Techniques

Macroscopic and microscopic spray properties can be measured using a range of optical techniques. A classical method for macroscopic properties is *back-light imaging* (BLI). A complementary approach is *planar laser imaging* (PLI). Both techniques can also be used for microscopic properties such as droplet size distribution with an appropriate setup. However, for droplet velocities other methods such as *laser Doppler anemometry* (LDA) is usually more suitable when the required equipment is available.

### 2.4.1 Back-light Imaging

BLI, also referred to as shadowgraph imaging, is one of the most common methods for characterizing spray properties and is a relatively simple optical technique [28]. The optical components include a light source such as a *light-emitting diode* (LED) illumination and an imaging system. The imaging system is typically a high-speed camera since a high frame rate is needed to achieve sufficient temporal resolution. A short exposure time is particularly important when measuring microscopic properties in order to avoid motion blur. An example setup is shown in Figure 2.6.



**Figure 2.6:** Example setup adapted from [31].

The working principle relies on the optical contrast created when light is refracted, reflected, and partially blocked by droplets relative to the surrounding medium. A bright background is created by the back illumination and the droplets appear as

dark regions or shadows against this background. As a result, there is a contrast difference between the droplets and the background. In true BLI, the illumination is placed behind the spray, producing a dark spray image on a bright background as illustrated in Figure 2.7a. Illumination from the side, although no longer being true BLI in the strict sense, can also be useful which produces a bright spray image on a dark background, shown in Figure 2.7b. Both of these will be referred to as BLI in this thesis, although true BLI in the literature usually refers specifically to illumination from behind.

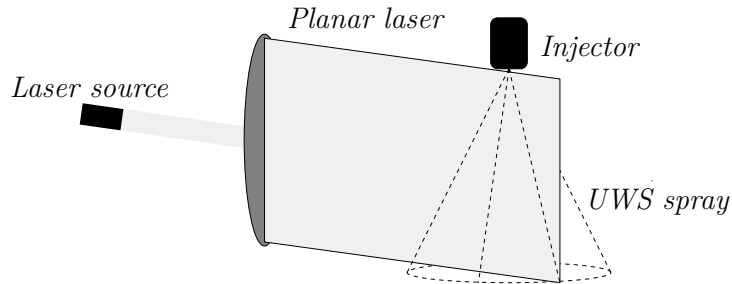


**Figure 2.7:** Image when placing illumination from behind (a) and from the side (b).

When microscopic properties are estimated using a high-speed camera, a macro lens is often required. This approach is referred to as *microscopic back-light imaging* (MBLI) [31]. Droplet velocity can, in principle, be estimated from multiple frames with known time difference by tracking individual droplets. For this to be achievable, a very high frames per second is required. This is less critical when estimating penetration length and spray cone angle, for which adequate contrast and sharpness are generally more important than extremely high temporal resolution.

### 2.4.2 Planar Laser Imaging

PLI, sometimes referred to as laser sheet imaging, is a technique in which a laser beam is reshaped into a planar laser slice, or a "sheet", that illuminates a cross-section of interest [29]. This can give insight of the type of spray, i.e. whether it is a hollow- or full-cone. Figure 2.8 illustrates the basic principle of the technique. The laser plane can be generated in different ways such as passing the laser beam through a divergent lens. A high-speed camera is still commonly used for high temporal sampling, just like BLI.



**Figure 2.8:** Basic principle of PLI.

# 3

## Methodology

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This chapter describes the methodology used in the project. First, the experimental setups are presented in detail. Next, the experimental procedures are described. Finally, the post-processing and analysis of the raw data are explained.

### 3.1 Experimental Setup

A glass container with dimensions of  $60 \times 60 \times 30$  cm was used to create a closed environment that protected surrounding equipment from UWS. The injector was positioned centrally at the top of the container, 15 cm from one wall, as shown in Figure 3.3, which presents the actual setup. The container size and injector placement were chosen so that no droplets would reach the wall facing the camera, which would otherwise have disturbed the image acquisition. The container height was selected to minimize droplet recirculation and swirl, since these could also disturb the measurements.

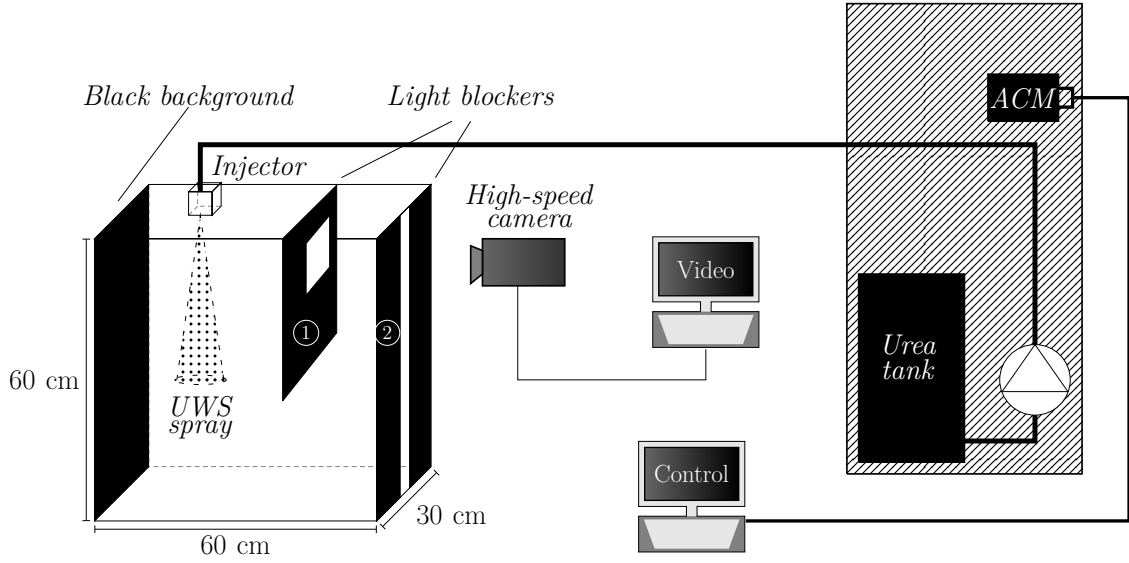
**Table 3.1:** *Specifications of the high-speed camera, Phantom v1210. At full resolution, maximum 12,000 fps can be achieved.*

| Parameter             | Value             | Unit           |
|-----------------------|-------------------|----------------|
| Sensor                | 1                 | Mpx            |
| Maximum resolution    | $1280 \times 800$ | px $\times$ px |
| Throughput            | 12                | Gpx/s          |
| Minimum exposure time | 1                 | $\mu$ s        |

Two separate computers were used in the setup. One controlled the high-speed camera, and the other was connected to the *after-treatment control module* (ACM) which in turn was connected to the urea tank and pump. This arrangement allowed control of both the injection pressure and the injection mass flow rate.

To determine the physical length corresponding to one pixel, an image of a lined paper placed at the injector location was captured. The number of pixels corresponding to a known distance was determined and used in subsequent image analysis requiring a known spatial resolution.

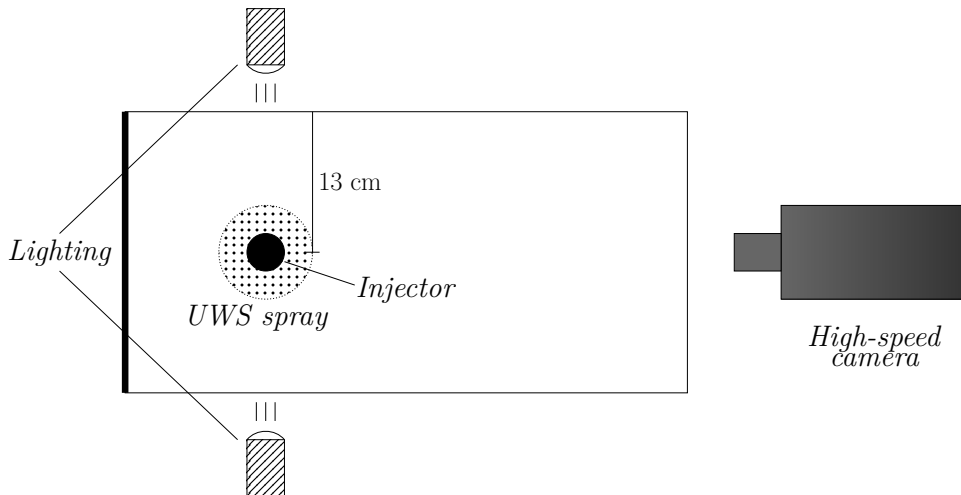




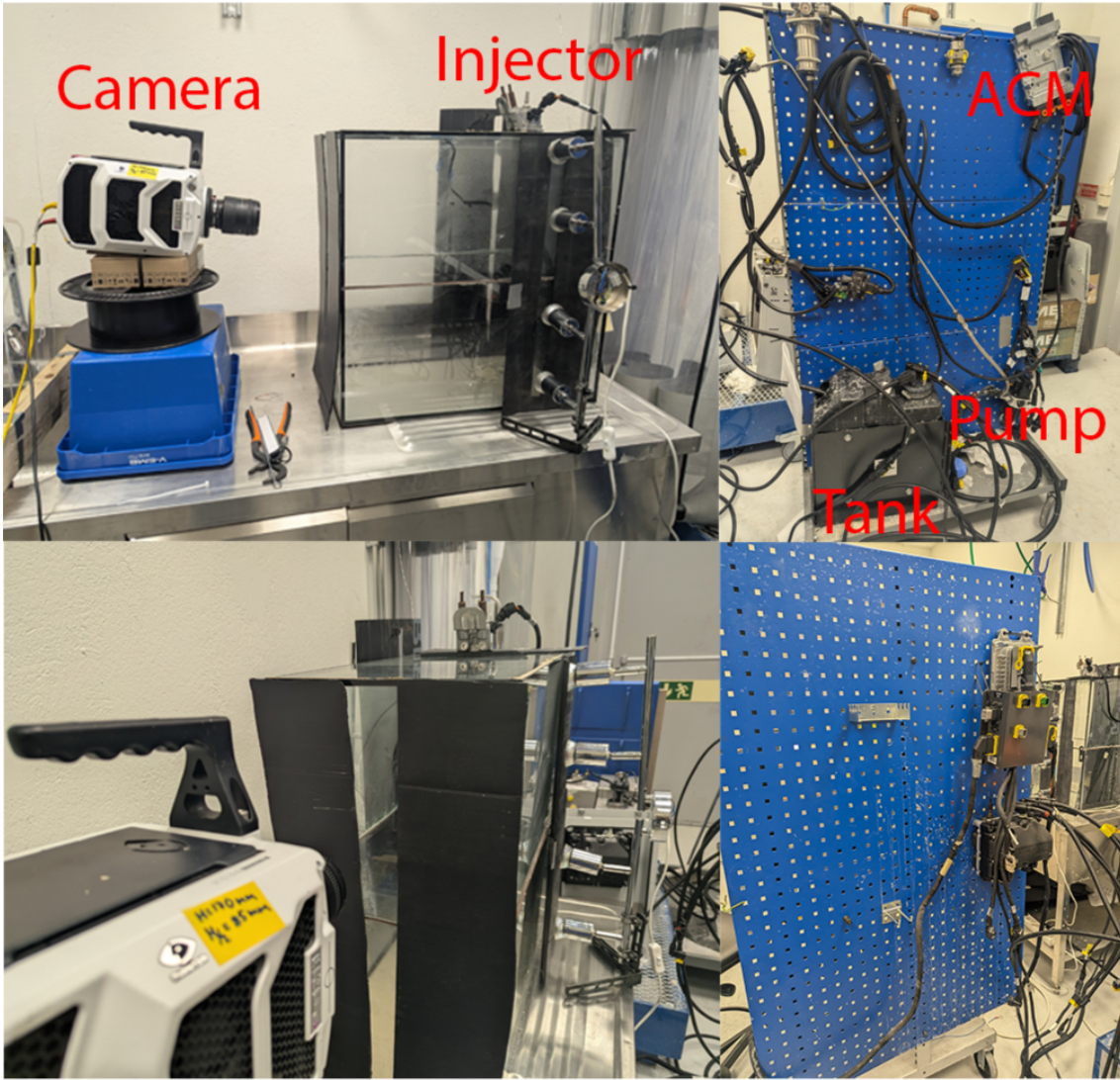
**Figure 3.1:** Sketch of the BLI and PLI setup. Light blocker 1 was used for spray cone angle measurements and light blocker 2 for penetration length measurements.

### 3.1.1 Back-light- and Planar Laser Imaging Setup

The high-speed camera was a Phantom v1210 with specifications in Table 3.1. The illumination sources consisted of either four 10 W LED spots on either side for BLI or a laser sheet for PLI. Their placement, together with that of the camera, is shown in Figure 3.2. Black screens were used for some measurements to enhance the contrast between spray and background and to minimize reflections inside the container. Black masks were also placed in front of the camera in different configurations depending on the measurement. The real setup in Figure 3.3 shows the specific setup for a penetration length measurement.



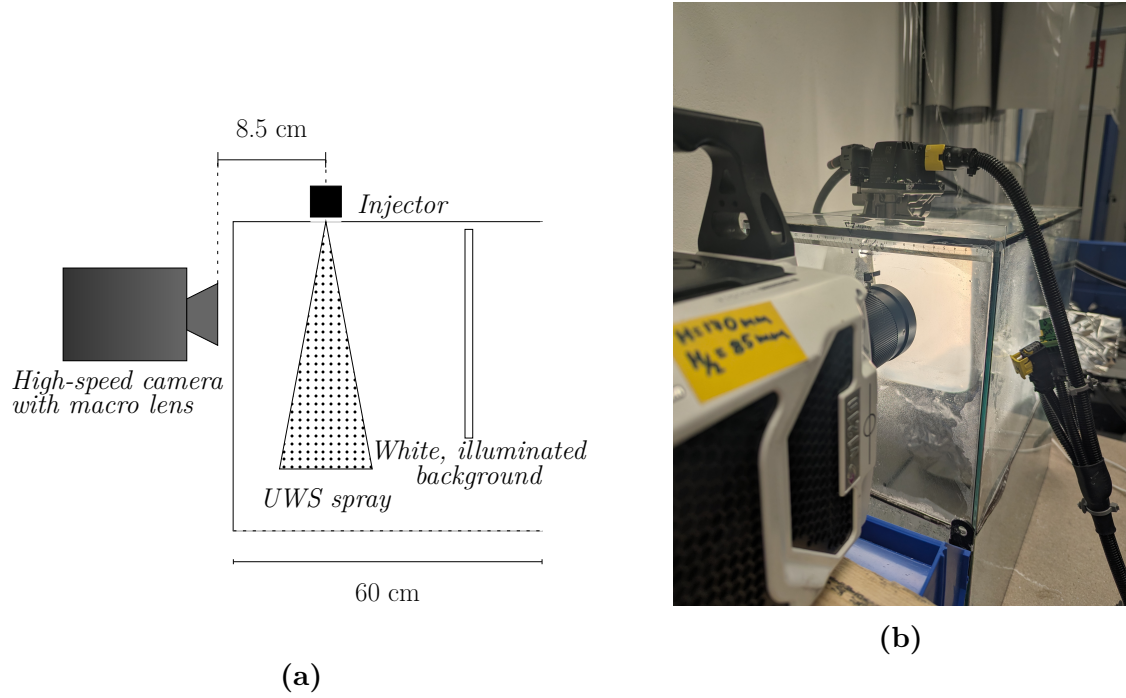
**Figure 3.2:** Simplified top view of the container, injector, lighting, and high-speed camera for BLI and PLI experiments. This lighting placement was used for spray cone angle and penetration length measurements.



**Figure 3.3:** Real BLI and PLI setup for penetration length measurements. Lower right image shows the rig wall for injector #2 which uses a different ACM and pump.

### 3.1.2 Microscopic Back-light Imaging Setup

The 2x macro lens available in the project had a working distance of 85 mm. To allow recording from one container side, the injector had to be placed closer to that container wall, as illustrated in Figure 3.4a, showing a schematic of the MBLI setup. The inside of the container wall was cleaned between each measurement series to remove optical disturbances. The real setup can be seen in Figure 3.4b. A white background, illuminated by eight 10 W LEDs, was placed on the opposite side of the camera. This yielded images with droplets that were dark on a bright background.



**Figure 3.4:** Sketch of the MBLI setup (a) and the real MBLI setup (b). The injector has been moved closer to the wall due to the focus length being 8.5 cm with the macro lens.

## 3.2 Experimental Procedure

The experimental parameters used for the BLI and PLI experiments are presented in Table 3.2, and those used for the MBLI experiments are given in Table 3.3. During estimations of penetration lengths and spray cone angle, all operating points were tested for both injectors. The fixed UWS pressure of 900 kPa was chosen due to this pressure being currently used in the real application. The injection temperature was constant at room temperature for penetration length and spray cone angle measurements.

**Table 3.2:** Test variations for BLI and PLI experiments.

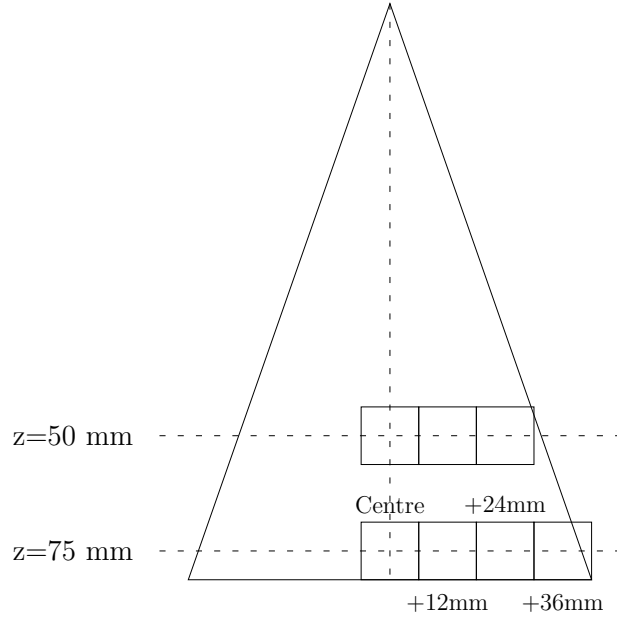
| Category        | Factor              | Range                     | Unit |
|-----------------|---------------------|---------------------------|------|
| Injector        | Injector type       | #1, #2                    | -    |
| Operating point | Mass-flow rate      | 0.2, 0.5, 0.8, 1.67, 3.33 | g/s  |
| Fixed           | UWS temperature     | RT                        | °C   |
| Fixed           | Pressure            | 900                       | kPa  |
| Fixed           | Fluid               | 32.5% UWS                 | -    |
| Fixed           | Injection frequency | 1                         | Hz   |

For the droplet size distribution, all spatial positions visualised in Figure 3.5 and all operating points were analysed for injector #1, assuming axisymmetry. Measurements at elevated injection temperature were performed for all radial

positions at  $z = 75$  mm with a mass-flow of 1.67 g/s for injector #1. The elevated temperature was achieved using an immersion heater positioned in a separate tank connected to the rig. All radial positions at  $z = 75$  mm were also tested for injector #2 to compare it with injector #1. For every setting, the first 3-100 ms after *start of injection* (SOI) was analysed during the first injection event.

**Table 3.3:** *Test variations for MBLI experiments.*

| Category           | Factor              | Range                     | Unit |
|--------------------|---------------------|---------------------------|------|
| Fixed              | Injector type       | #1, #2                    | -    |
| Operating point    | Mass-flow rate      | 0.2, 0.5, 0.8, 1.67, 3.33 | g/s  |
| Measurement point  | Radial position     | Centred, +12, +24, +36    | mm   |
| Measurement point  | Axial position      | 50, 75                    | mm   |
| Boundary condition | UWS temperature     | RT, 40                    | °C   |
| Fixed              | Pressure            | 900                       | kPa  |
| Fixed              | Fluid               | 32.5% UWS                 | -    |
| Fixed              | Injection frequency | 1                         | Hz   |



**Figure 3.5:** *Spatial positions for sampling of droplet size in the spray for the MBLI experiments.*

Droplet velocity was, similarly to droplet size, analysed for a mass-flow of 1.67 g/s for all spatial positions at room temperature for injector #1. Droplet velocity was also estimated for the elevated temperature with injector #1 and with injector #2 at room temperature for all radial positions at  $z = 75$  mm. The velocity was analysed at 100 ms after SOI for all settings.

Subsequent analysis of the captured raw images and data was performed with various Python scripts which are described in the next section.

### 3.2.1 Penetration Length and Spray Cone Angle with BLI

For penetration length measurements, the high-speed camera was positioned to capture the full height of the container, using the settings presented in Table 3.4. For spray cone angle measurements, the camera was positioned to capture the upper part of the spray, using the settings presented in Table 3.5. UWS was injected into the container while one parameter at a time was varied and the others were kept constant, and the first injection event was recorded.

**Table 3.4:** *High-speed camera settings used for BLI experiments to estimate penetration length.*

| Parameter                    | Value                               | Unit        |
|------------------------------|-------------------------------------|-------------|
| Image acquisition frequency  | 6000                                | fps         |
| Image resolution             | 1280×800                            | pixel×pixel |
| Spatial resolution           | 666.67                              | μm/pixel    |
| Exposure time                | 160                                 | μs          |
| Lens                         | AF Zoom-Nikkor 24-85 mm f/2.8-4D IF | -           |
| Distance, sensor to injector | 68                                  | cm          |

**Table 3.5:** *High-speed camera settings used for BLI experiments to estimate spray cone angle.*

| Parameter                    | Value                               | Unit        |
|------------------------------|-------------------------------------|-------------|
| Image acquisition frequency  | 2000                                | fps         |
| Image resolution             | 1280×800                            | pixel×pixel |
| Exposure time                | 490                                 | μs          |
| Lens                         | AF Zoom-Nikkor 24-85 mm f/2.8-4D IF | -           |
| Distance, sensor to injector | 45                                  | cm          |

### 3.2.2 Droplet Size and Velocity with MBLI

To resolve individual droplets, the field of view was significantly reduced by using a macro lens. The remaining settings are presented in Table 3.6. UWS was injected according to the previously described cases, and the first injection was recorded using the high-speed camera.

**Table 3.6:** *High-speed camera settings used for MBLI experiments to estimate droplet size and droplet velocity.*

| Parameter                   | Value                           | Unit        |
|-----------------------------|---------------------------------|-------------|
| Image acquisition frequency | 19000                           | fps         |
| Image resolution            | 768×768                         | pixel×pixel |
| Spatial resolution          | 15.6                            | μm/pixel    |
| Exposure time               | 7                               | μs          |
| Lens                        | Ttartisan 100 mm F/2.8 Macro 2x | -           |
| Distance sensor to injector | 22.5                            | cm          |

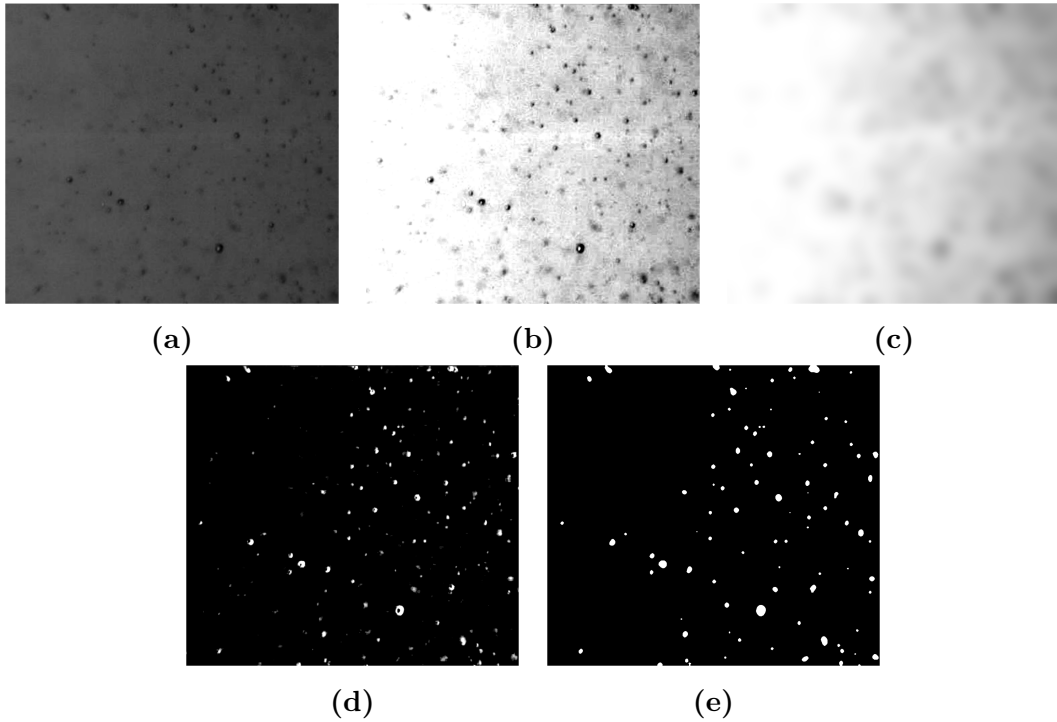
### 3.3 Data Analysis

Post-experimental data, mainly in the form of raw images, were analysed using various Python scripts written during this project. All scripts are presented in Appendix B, where selected parts of the code are commented. The main processing procedures are described below.

#### 3.3.1 Droplet Size

A Python script for extracting droplet data from images was developed based on a previous MATLAB script written by Omar Moussa et al. [31]. The script consisted of two main steps: raw image processing to a binarized image, and droplet detection.

The raw image processing steps are illustrated in Figure 3.6. First, the contrast was adjusted, making the background brighter and the droplets darker, as shown in Figure 3.6b. Next, a Gaussian-filtered version of the image was generated as shown in Figure 3.6c, and subtracted from the contrast-enhanced image. In this context, the Gaussian-filtered image can be viewed as a blurred version of the original image. The colours were then inverted so that the droplets appeared white and the background black, as shown in Figure 3.6d, which facilitated the subsequent binarization. Some droplets were inevitably out of focus and should not be included, since their sizes tend to be overestimated. These were filtered out using Wiener and median filtering before finally creating a binarized image, shown in Figure 3.6e.



**Figure 3.6:** *Processing of raw image (a) by contrast adjustment (b), subtracting the Gaussian filter (c) and inverting colours (d), and filtering and binarization (e).*

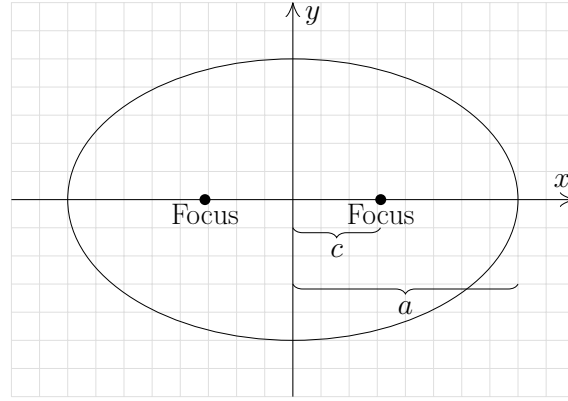
All blob areas, that is the white regions in Figure 3.6e, were detected and calculated by the script. However, not all detected blobs satisfied the morphology criteria for droplets and therefore had to be filtered out. This was done using both circularity and eccentricity. Circularity is defined as

$$C = \frac{4\pi A}{P^2} \quad (3.1)$$

where  $A$  and  $P$  are the blob area and perimeter, respectively. Eccentricity is the ratio between the distance to the foci and the major axis length [32],

$$e = \frac{c}{a} \quad (3.2)$$

and is illustrated in Figure 3.7.



**Figure 3.7:** An ellipse with marked foci, whose sum of distances to any point on the ellipse is constant. The ratio of distances  $c$  and  $a$  make up the eccentricity.

The accepted circularity and eccentricity were set to  $0.8 < C < 1.8$  and  $e < 0.85$ , respectively. For a circle  $C = 1$  and  $e = 0$ . In digital image analysis, circularities slightly above 1 may occur because of pixelation and contour-estimation errors. Therefore, a tolerance above 1 was allowed in the filtering criterion. In addition to the morphology filter, a focus filter was incorporated to exclude out-of-focus droplets, since these tend to be overestimated in size. This was done by evaluating the average pixel intensity of each blob and the fraction of bright pixels within each blob in the non-binarized image. By applying this algorithm over multiple raw images, an accumulated array of droplet diameters was obtained. The images were selected from the first 3-100 ms after SOI. Double counting of droplets was avoided by using an interval of 40 frames between selected images. Approximately 65 images per experiment were analysed. Based on all detected droplets, histograms over the droplet diameters were constructed together with the metrics discussed in the theory chapter.

To compare the droplet size differences between the two injectors and between the two temperatures, Welch's t-test was carried out. First, the test statistic,

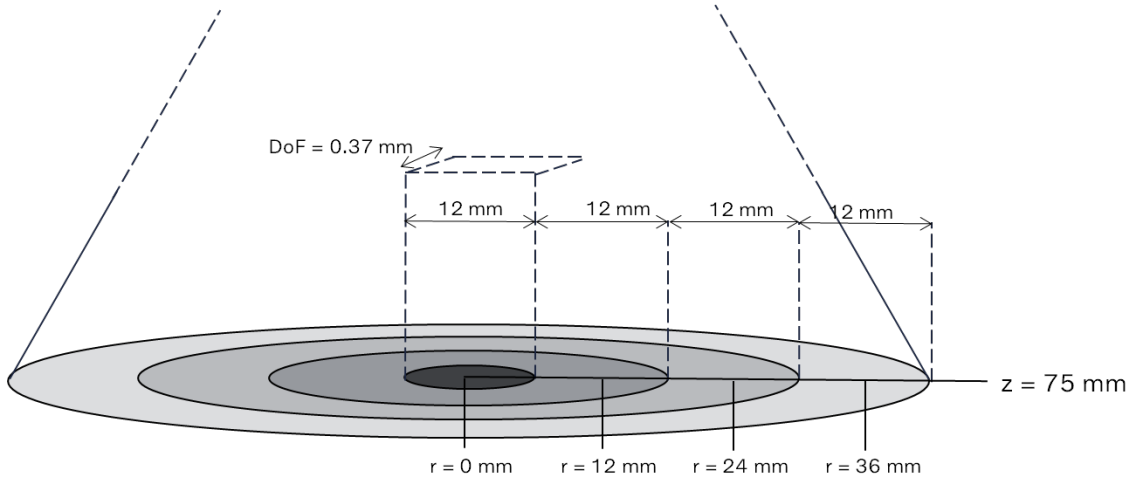
$$t = \frac{\bar{d}_1 - \bar{d}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \quad (3.3)$$

was calculated were  $s$  is the sample standard deviation and  $n$  is the sample size. Statistical significance was assessed at a significance level of 0.05. The benefit of using Welch's t-test is that the population size will most likely differ. It also assumes that the droplets are independent observations.

Finally, to estimate the equivalent number of droplets on each annulus, illustrated in Figure 3.8, the detected number of droplets from each radial position was multiplied by the fraction of each annulus area and the product of the depth of field of the camera and the interval width as,

$$N_{\text{droplet,annulus},i} = A_{\text{annulus},i} \cdot \frac{N_{\text{detected droplets}}}{\text{DoF} \cdot 12 \text{ mm}}. \quad (3.4)$$

This assumes that the droplets passing each interval are evenly distributed over all disk areas. All scaling factors, that is the factor multiplied with  $A_{\text{annulus},i}$  are presented in Table 3.7 alongside each annulus area.



**Figure 3.8:** *Cut-through of the spray from injector #1 at  $z = 75$  mm.*

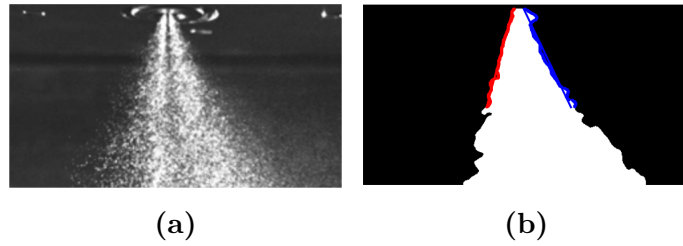
**Table 3.7:** *Areas and scaling factors for each annulus in Figure 3.8.*

| Annulus | Area (mm <sup>2</sup> ) | Scaling factor |
|---------|-------------------------|----------------|
| 1       | 113.1                   | 25.5           |
| 2       | 904.8                   | 203.8          |
| 3       | 1809.6                  | 407.6          |
| 4       | 2714.3                  | 611.3          |



### 3.3.2 Spray Cone Angle

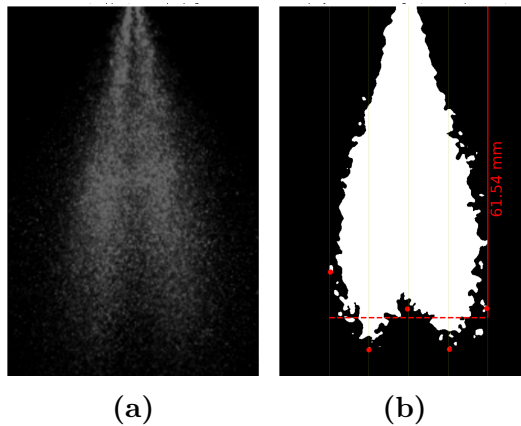
The first part of the spray cone angle script consisted of an image processing similar to that ~~one~~ used for droplet size analysis. After binarization of the image, the spray cone angle was measured by identifying the outer coordinates of the spray from the nozzle exit down to a height of  $z = 25$  mm and fitting two lines to these coordinates. The angle between these lines was then calculated which defined the spray cone angle. Figure 3.9 shows an example of a raw image together with the final result of the script, including the measured cone angle. By repeating this procedure for approximately 100 images of a developed spray, an average of the spray cone angle was obtained.



**Figure 3.9:** Example of a raw image (a) and measured cone angle on the binarized version after image processing (b).

### 3.3.3 Penetration Length

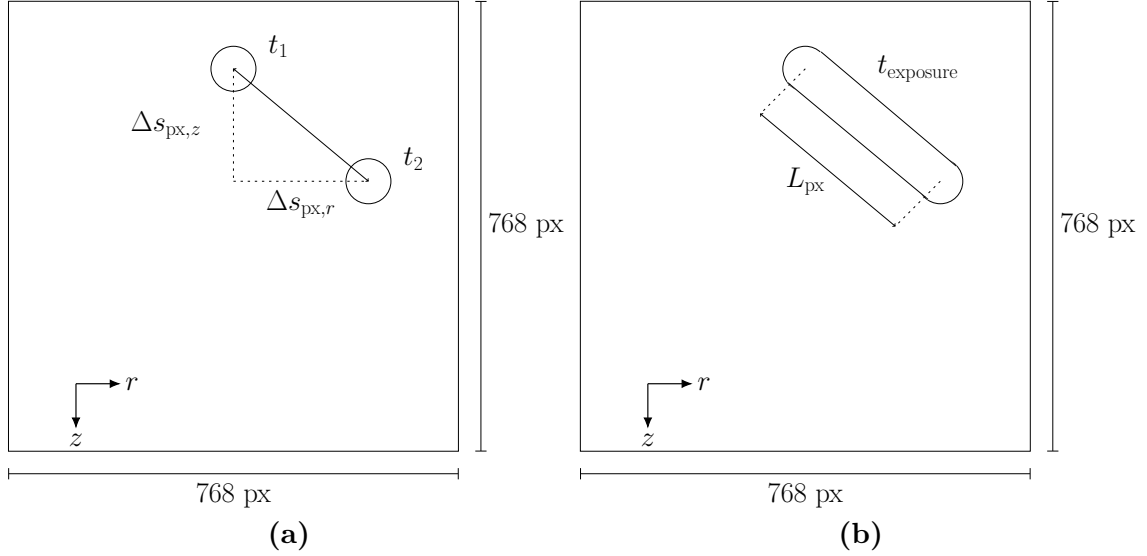
Measurement of the penetration length was performed in a similar manner to that used for the spray cone angle. The width of the spray was determined by identifying the two white pixels furthest from the centreline on each side. To account for morphological variations and to reduce possible errors from the binarization process, the spray was divided into intervals of 50 fixed horizontal positions. A mean z-value of these positions was taken as the penetration length. Figure 3.10 illustrates how an example raw image was used to calculate the penetration length, where only five horizontal positions are shown for clarity.



**Figure 3.10:** Raw example image (a) and measured penetration length on the binarized image after image processing (b).

### 3.3.4 Droplet Velocity

Two Python scripts were written to estimate droplet velocity from images captured by the high-speed camera, and the results were later compared. The first script used images captured with an exposure time of 6  $\mu\text{s}$ , as illustrated in Figure 3.11a. The second script used images captured with an exposure time of 25  $\mu\text{s}$  to achieve motion blur and droplets looking like lines, as is illustrated in Figure 3.11b. Image processing to obtain binary images from a set of raw images were performed as previously.



**Figure 3.11:** Illustrations of manual estimation of droplet velocity with low exposure time leading to distinct droplets (a) and high exposure time causing motion blur and droplets in the forms of lines (b).

Knowing the length per pixel in meters,  $mpp$ , the time difference between the frames, and measuring the axial and radial pixel differences,  $\Delta s_{px,z}$  and  $\Delta s_{px,r}$ , the axial and radial velocity can be calculated as

$$u_z = \frac{\Delta s_{px,z} \cdot mpp}{\Delta t} \quad (3.5)$$

and

$$u_r = \frac{\Delta s_{px,r} \cdot mpp}{\Delta t}, \quad (3.6)$$

respectively. Similarly for the measurements with higher exposure time, the absolute velocity was estimated from the line length in Figure 3.11b as

$$|u| = \frac{L_{px} \cdot mpp}{t_{\text{exposure}}}. \quad (3.7)$$

The droplet diameter for these measurements were taken as the average width of the line.

# 4

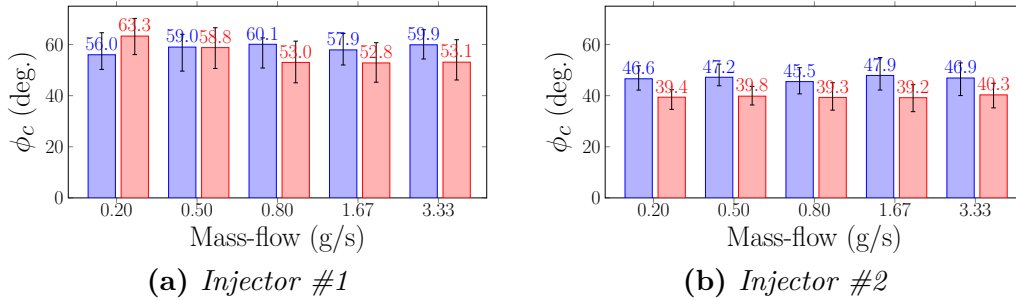
## Results and Discussion

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This chapter is divided into sections addressing the effects of UWS mass-flow, measurement position, UWS temperature, and injector type on the spray metrics obtained from the BLI, PLI, and MBLI experiments. This is followed by an evaluation of the observed differences between the velocity measurement techniques. Selected images used for the generated plots are presented in Appendix A.

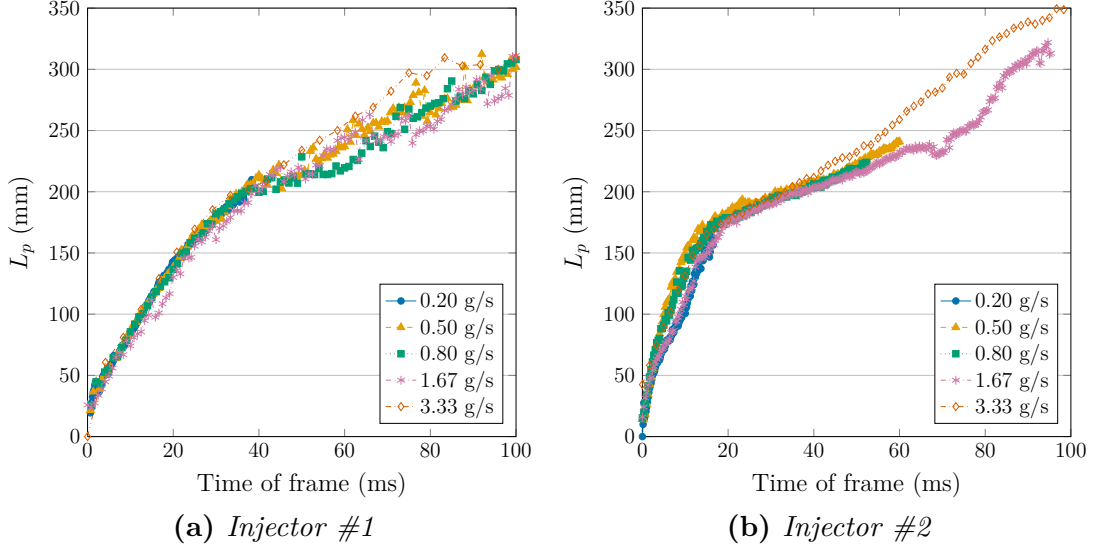
### 4.1 Effect of UWS Mass-flow

Varying the UWS mass-flow for both injectors produced little noticeable difference in the spray cone angle by visual inspection. Analysis of the captured images using the Python script showed only small differences in spray cone angle, as presented in Figure 4.1. Comparing the measurements between BLI and PLI, it was observed that PLI generally resulted in slightly lower angles, except for the measurement at 0.20 g/s for injector #1. One plausible explanation for the lower angles with PLI is that, since PLI captures only one plane of the spray, the measured angle may be underestimated if the laser sheet is not perfectly centred. This issue does not arise in the same way for BLI, since the entire spray interacts with the light source. Another possible explanation is that smaller droplets near the spray edges may scatter less light and therefore be less visible in the PLI images. However, regardless of measurement technique, the spray cone angle varied only slightly. The results therefore indicate that the UWS mass flow rate had only a minor effect on the spray cone angle.



**Figure 4.1:** Spray cone angle measured with BLI and PLI for injector #1 (a) and injector #2 (b). The black bars indicate the minimum and maximum values.

Figure 4.2 shows the penetration length as a function of time. No distinct difference was observed when varying the UWS mass-flow rate for either injector. The overall pattern and graph shape are similar to those reported by Omar Moussa et al. for various mass-flow rates using a different injector, although only the first 20 ms were presented in that study. This indicates that the penetration length was not strongly affected by the UWS mass-flow rate. Due to the injection signal for the dosing, the penetration length will also be governed by the time that the injector is open, which is particularly evident for the case of 0.20 g/s in Figure 4.2.



**Figure 4.2:** Penetration length against time of frame for injection at different mass-flows with injector #1 (a) and injector #2 (b).

For both injectors, it can be observed that the increase in penetration length was greatest shortly after SOI. Afterwards, the curve took a more plateau-like shape. As for the penetration length itself, no significant difference between the mass-flow cases was observed for this initial increase.

The droplet size measurement data centred at  $z = 50$  mm for injector #1 at different mass-flow rates are presented in Table 4.1. It can be seen that more droplets were detected at the higher mass-flow rates, which were also associated with a lower SMD. The decrease in SMD may be due to the transient phase constituting a smaller fraction of the analysed interval at higher mass flow rates. The variance relative to the arithmetic mean diameter is relatively high for many mass-flow rates. This may be because the measured droplet population is broad and includes both larger droplets from the earlier, less-developed part of the spray and smaller droplets from the more developed phase. The spread may also be amplified by the limited number of detected droplets and by the lower size-detection limit of the optical setup.

#### 4. Results and Discussion

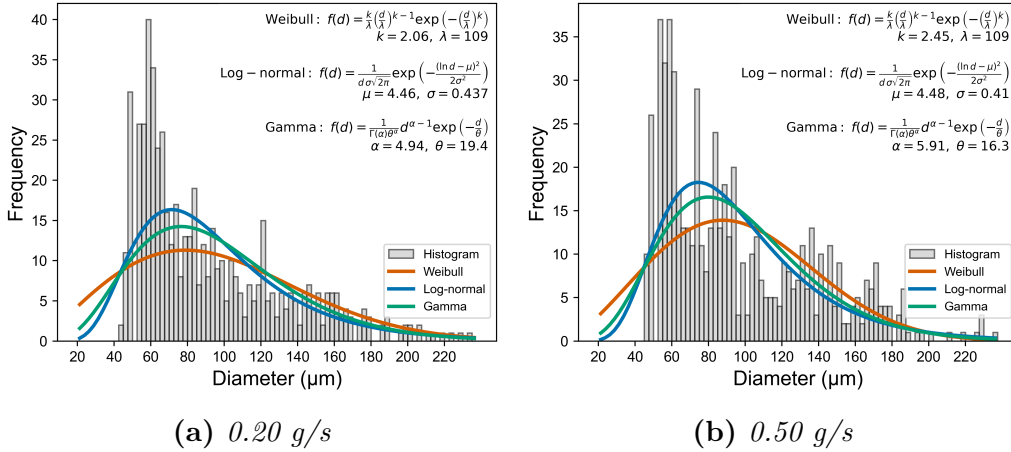
**Table 4.1:** Droplet size metrics ( $\mu\text{m}$ ) for injector #1 at  $z = 50$  mm and room temperature for different UWS mass flow rates, 3 to 100 ms after SOI.

| Mass-flow (g/s) | $N_{\text{droplets}}$ | SMD    | $\bar{d}$ | $\sigma$ | $d_{10}$ | $d_{50}$ | $d_{90}$ |
|-----------------|-----------------------|--------|-----------|----------|----------|----------|----------|
| 0.20            | 576                   | 156.62 | 95.95     | 49.73    | 52.81    | 79.69    | 159.40   |
| 0.50            | 610                   | 133.23 | 96.11     | 41.85    | 52.81    | 84.42    | 160.46   |
| 0.80            | 552                   | 122.13 | 88.06     | 37.12    | 52.81    | 78.72    | 142.90   |
| 1.67            | 513                   | 128.99 | 90.55     | 40.58    | 52.81    | 76.73    | 151.22   |
| 3.33            | 857                   | 129.28 | 89.67     | 74.68    | 52.81    | 74.68    | 150.60   |

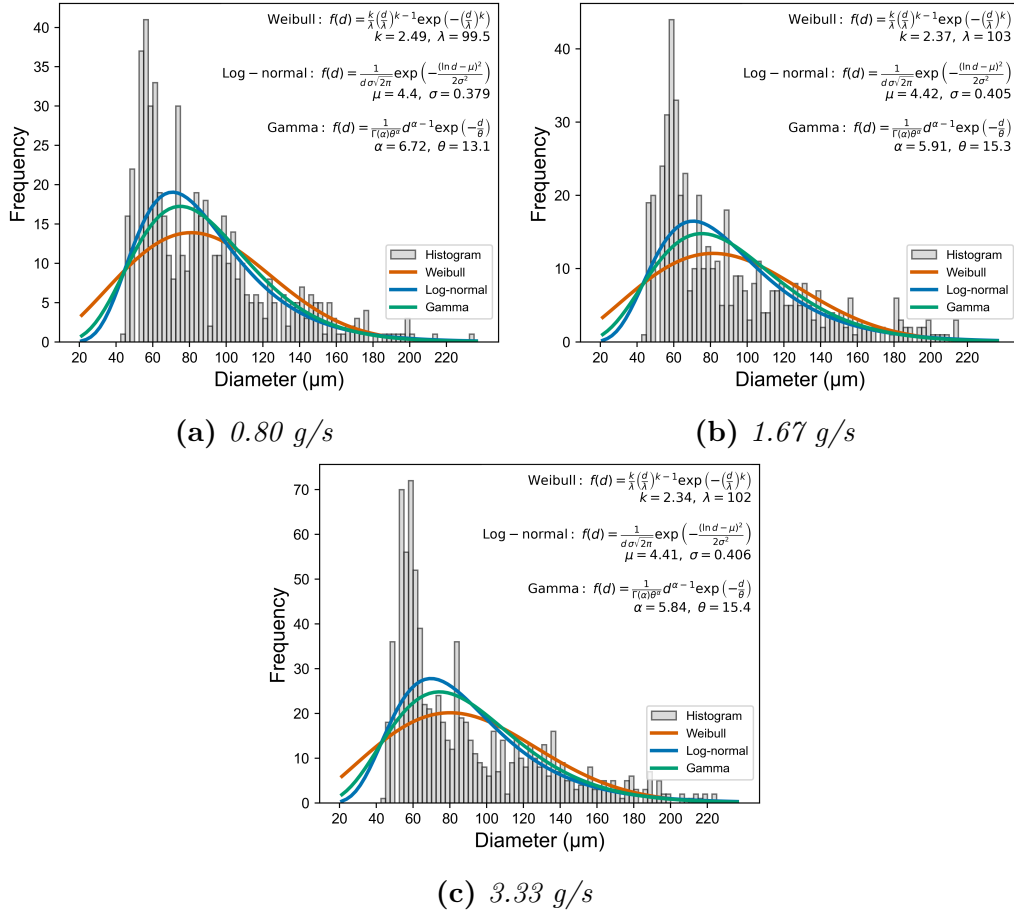
A notable result in Table 4.1 is that  $d_{10} = 52.81$   $\mu\text{m}$  for all cases, which also recurred in later measurements. This likely indicates a limitation in the spatial resolution of the current experimental setup. A lens with a greater magnification would likely affect this value. However, such a change would also reduce the number of droplets captured within the same number of images.

It was also observed that the SMD was larger in the first selected frames and that fewer droplets were detected in those frames. One possible explanation is that larger droplets tend to retain a slightly higher velocity, and therefore a greater proportion of them may appear in the earliest analysed frames, resulting in a larger SMD based on a smaller number of larger droplets. In addition, the first frames are closer to the transient phase, during which the spray is less developed and the droplets are likely to be larger and less uniformly distributed.

Histograms showing the variations more clearly are presented in Figures 4.3 and 4.4, together with fitted distributions. For all cases, log-normal distribution described the histogram best, whereas the Weibull distribution gave the poorest fit.



**Figure 4.3:** Droplet size distributions for injector #1 centrally at  $z = 50$  mm and mass-flow rates of 0.20 and 0.50 g/s, 3 to 100 ms after SOI.



**Figure 4.4:** Droplet size distributions for injector #1 centrally at  $z = 50$  mm and mass-flow rates of 0.80, 1.67, and 3.33 g/s, 3 to 100 ms after SOI.

In summary, varying the UWS mass-flow rate had no noticeable effect on penetration length or spray cone angle for either injector. However, the droplet size distribution for injector #1 appeared to depend on mass-flow rate, with both the SMD and the arithmetic mean diameter decreasing as the mass flow rate increased from the lowest to the highest tested values.

## 4.2 Effect of Axial and Radial Position

For the seven spatial positions analysed, both the number of droplets and the droplet size metrics varied, as shown in Tables 4.2 and 4.3. The corresponding droplet-size histograms are presented in Figures 4.5 and 4.6. More droplets were detected farther from the spray centreline at both axial positions,  $z = 50$  mm and  $z = 75$  mm. At the same time, both the SMD and the arithmetic mean diameter decreased radially, indicating that the larger droplets tended to remain closer to the spray centre. The higher number of droplets detected farther from the centreline also supports the hollow cone character of the spray, as expected from injector #1.

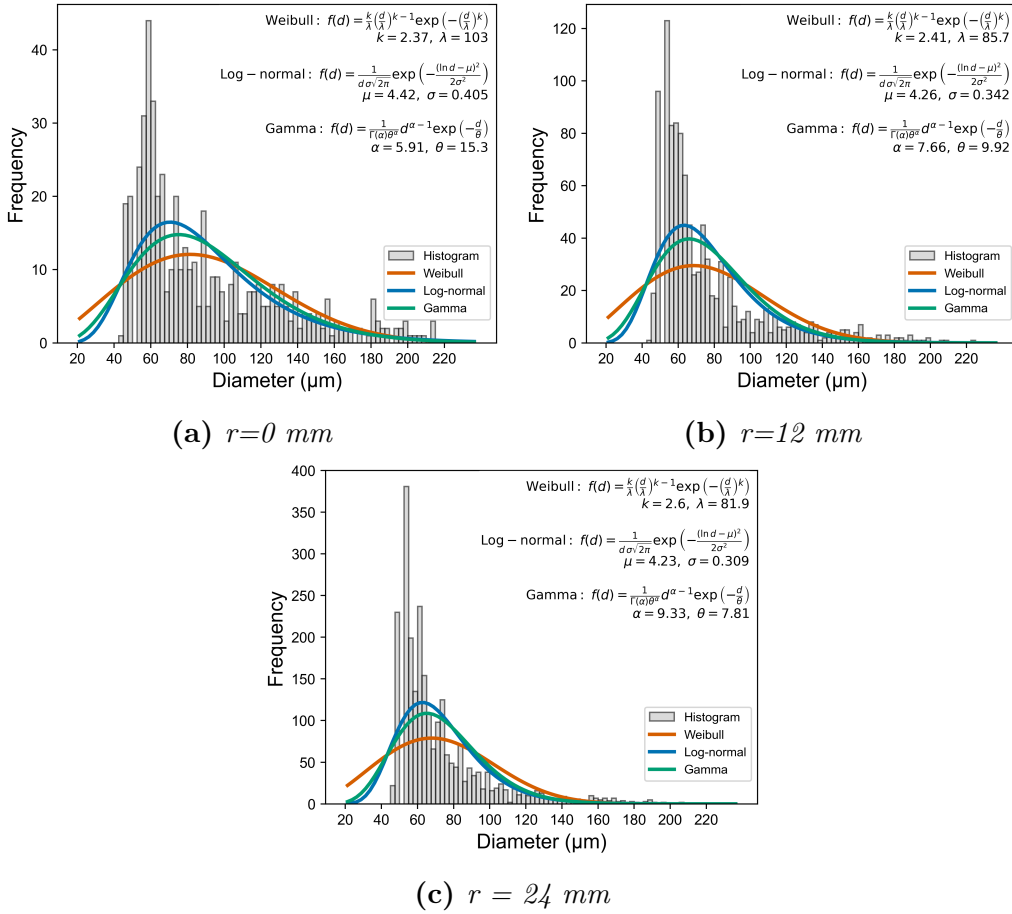
## 4. Results and Discussion

**Table 4.2:** Droplet size metrics ( $\mu\text{m}$ ) for injector #1 at  $z = 50$  mm, 1.67 g/s, and room temperature at different radial positions, 3 to 100 ms after SOI.

| Radial Position (mm) | $N_{\text{droplets}}$ | SMD    | $\bar{d}$ | $\sigma$ | $d_{10}$ | $d_{50}$ | $d_{90}$ |
|----------------------|-----------------------|--------|-----------|----------|----------|----------|----------|
| 0                    | 513                   | 128.99 | 90.55     | 40.58    | 52.81    | 76.73    | 151.22   |
| 12                   | 1034                  | 109.70 | 75.97     | 32.30    | 49.79    | 63.47    | 122.84   |
| 24                   | 2486                  | 99.72  | 72.92     | 28.04    | 49.79    | 63.47    | 108.51   |

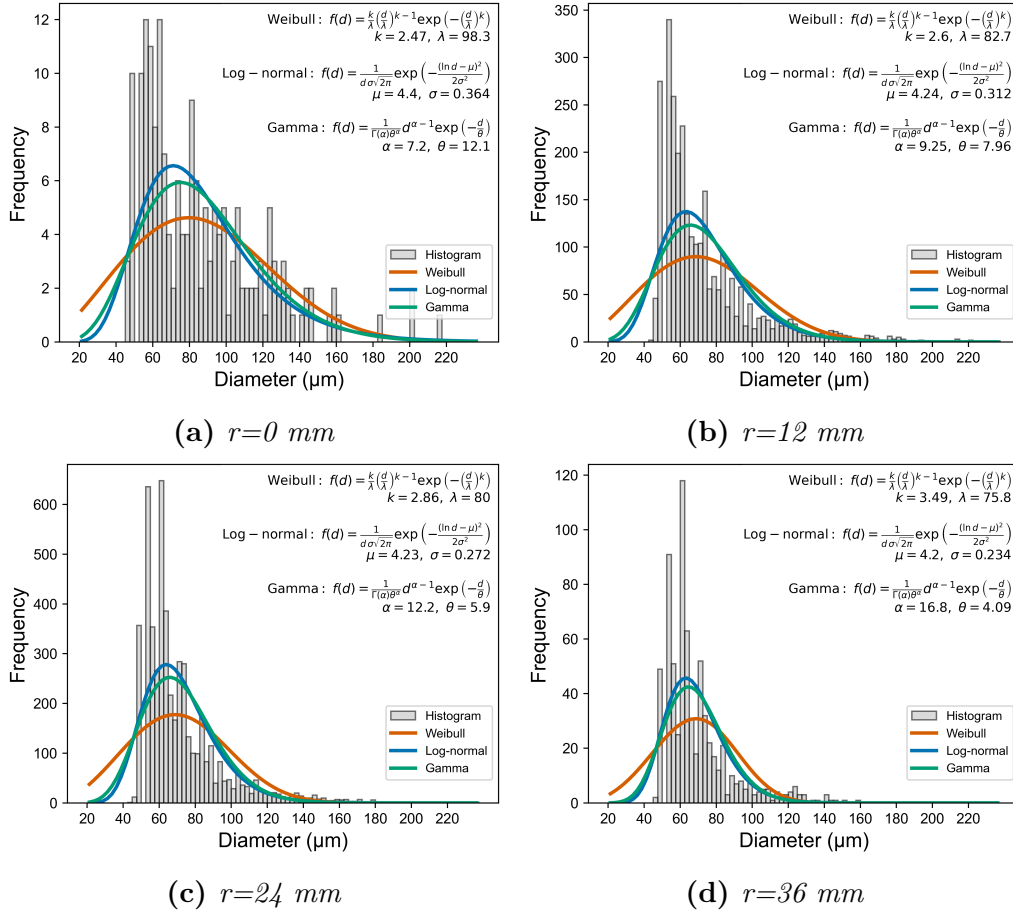
**Table 4.3:** Droplet size metrics ( $\mu\text{m}$ ) for injector #1 at  $z = 75$  mm, 1.67 g/s, and room temperature at different radial positions, 3 to 100 ms after SOI.

| Radial Position (mm) | $N_{\text{droplets}}$ | SMD    | $\bar{d}$ | $\sigma$ | $d_{10}$ | $d_{50}$ | $d_{90}$ |
|----------------------|-----------------------|--------|-----------|----------|----------|----------|----------|
| 0                    | 183                   | 122.64 | 87.16     | 36.32    | 52.81    | 78.72    | 130.55   |
| 12                   | 2858                  | 100.54 | 73.64     | 28.27    | 49.79    | 63.47    | 111.33   |
| 24                   | 5040                  | 92.04  | 71.75     | 23.94    | 52.81    | 63.47    | 101.12   |
| 36                   | 697                   | 80.57  | 68.72     | 18.68    | 52.81    | 63.47    | 93.14    |



**Figure 4.5:** Droplet size distributions for injector #1 at different radial positions at  $z = 50$  mm and 1.67 g/s, 3 to 100 ms after SOI.

## 4. Results and Discussion



**Figure 4.6:** Droplet size distributions for injector #1 for different radial positions at  $z = 75 \text{ mm}$  and  $1.67 \text{ g/s}$ , 3 to 100 ms after SOI.

Comparing the same radial position at the two axial locations, it can be noted that both the SMD and arithmetic mean diameter decreased when moving from  $z = 50 \text{ mm}$  to  $z = 75 \text{ mm}$ . This decrease suggests continued secondary breakup and/or evaporation as the spray developed downstream. The variance was also lower at  $z = 75 \text{ mm}$  than at  $z = 50 \text{ mm}$ , indicating that the droplets were more uniform farther downstream.

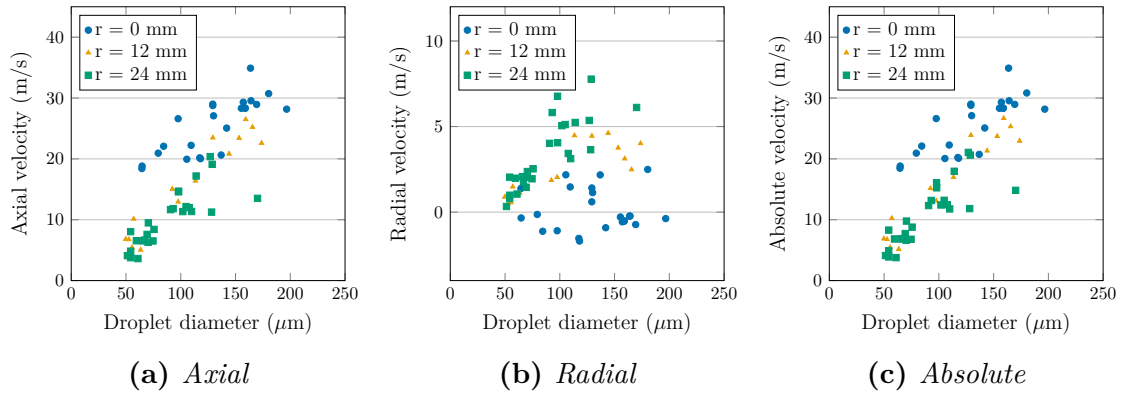
When analysing the raw images, the centrally located images were noticeably darker than the images farther from the centreline. This was especially apparent when comparing the two central positions at  $z = 50 \text{ mm}$  and  $z = 75 \text{ mm}$ . This is likely due to the hollow nature of the spray, which causes the outer part of the cone to appear out of focus when the images are captured at the spray centre. This may have affected the true number of droplets detected.

As observed later, the droplet velocity was higher near the centre of the spray. This affects how easily droplets can be detected, since the Python code applies morphological constraints to the detected droplet shapes. A higher velocity therefore likely made droplet detection more difficult in the central positions because of increased motion blur or deformation in the recorded images. To reduce

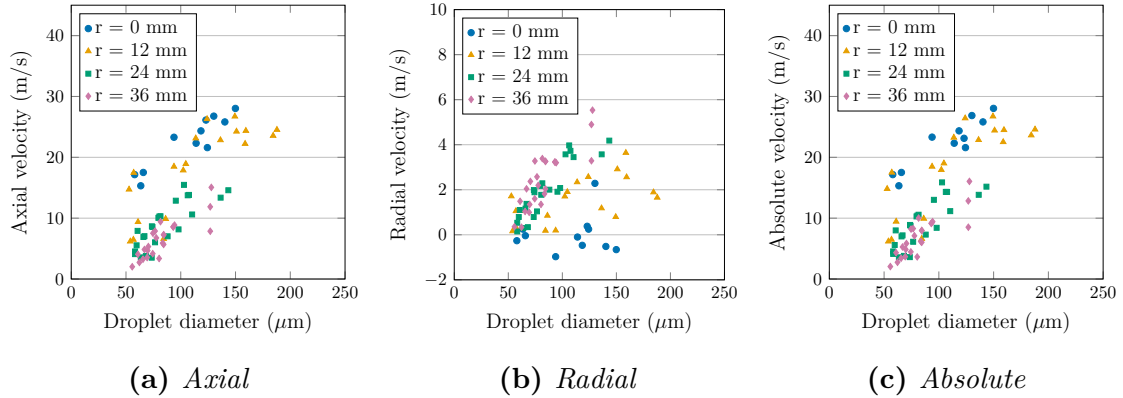


this effect, stronger illumination would be needed in order to allow a shorter exposure time.

Manual velocity estimation showed that both the absolute and axial velocity decreased radially, while the radial velocity increased radially, as shown in Figures 4.7 and 4.8 for  $z = 50$  mm and  $z = 75$  mm, respectively. Higher velocities centrally may be explained by there existing fewer droplets there, causing lower resistance. These higher velocities could also be a possible explanation for why droplet detection was more difficult at the central positions. It was also observed that larger droplets had higher velocity than smaller droplets. This is reasonable, since larger droplets retain their momentum more effectively, and are less influenced by aerodynamic drag.



**Figure 4.7:** *Estimated velocities at  $z = 50$  mm at different radial positions.*



**Figure 4.8:** *Estimated velocities at  $z = 75$  mm at different radial positions.*

Comparing the velocities between the two axial positions, differences were observed mainly at the central position, although these differences were relatively small. A decrease in velocity with axial distance is expected, and it is possible that this was most clearly observed at the central position because the axial velocity was highest there.

With the velocities, Weber numbers can also be estimated by taking the absolute velocities as a relative velocity between the droplets and the stagnant air. At  $z = 50$

mm, the highest and lowest observed value was 1.73 and 0.0172, respectively. At  $z = 75$  mm the highest and lowest observed value was 1.38 and 0.0101, respectively. This indicates that most secondary breakup had already occurred by  $z = 50$  mm.

Overall, the results indicate a clear spatial dependence of the spray characteristics, with smaller and more numerous droplets observed farther from the centreline and a modest downstream reduction in droplet size. The droplet velocity did not decrease substantially between the two axial positions. At  $z = 75$  mm the axial droplet velocity varied approximately between 5 m/s and 30 m/s.

### 4.3 Effect of UWS Temperature

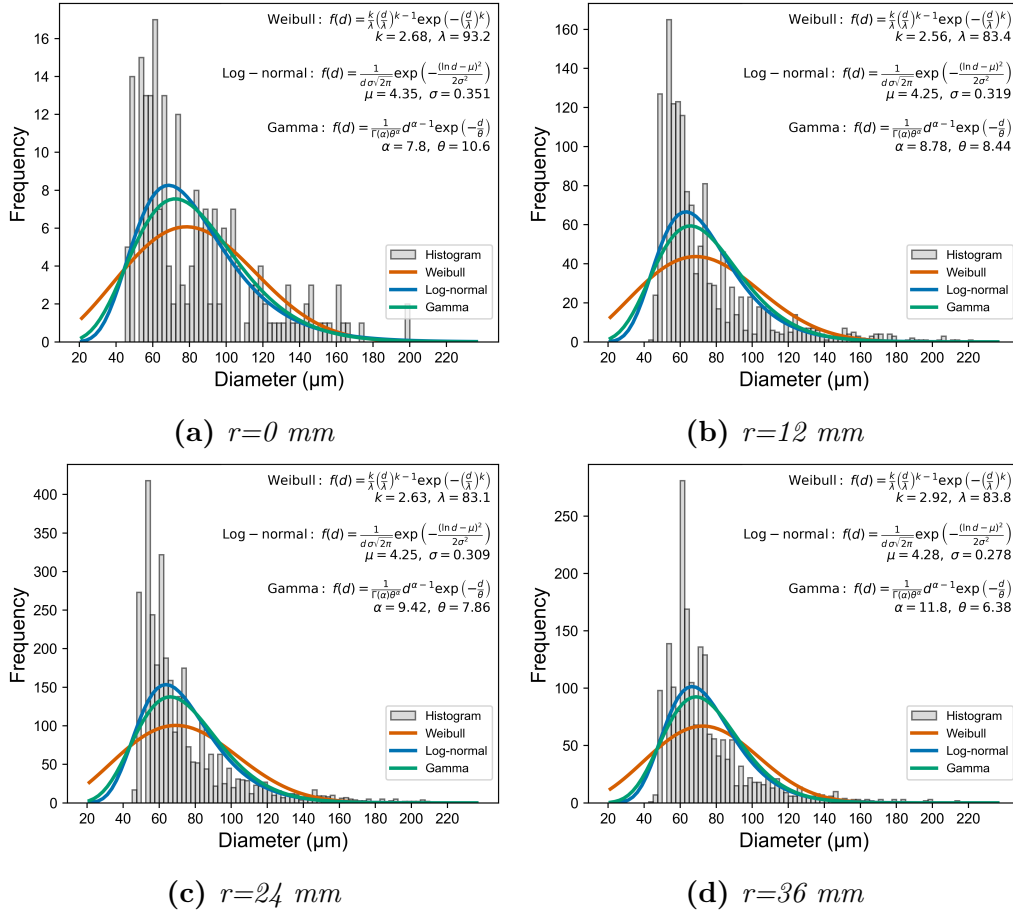
Repeating the measurements at a mass-flow rate of 1.67 g/s for the spatial positions at  $z = 75$  mm with injector #1 and an injection temperature of 40 °C suggested that the droplet size was more evenly distributed radially across the spray, as shown in Table 4.4. For the radial positions 24 and 36 mm, the SMD was higher, although more droplets were also detected at the radial position of 36 mm. Welch’s t-test showed that the droplet size difference between the two temperatures was significant only at the radial positions 24 mm and 36 mm, at the 0.05 significance level. As mentioned in the methodology, this test assumes independent observations, which may not be strictly valid when analysing droplets from the same injection event. Including droplets from a larger number of injections would therefore strengthen the statistical basis of the comparison, but this was not done due to the associated computation time.

**Table 4.4:** *Droplet size metrics ( $\mu\text{m}$ ) for injector #1 at  $z = 75$  mm, 1.67 g/s, 40 °C at different radial positions, 3 to 100 ms after SOI.*

| Radial Position (mm) | $N_{\text{droplets}}$ | SMD    | $\bar{d}$ | $\sigma$ | $d_{10}$ | $d_{50}$ | $d_{90}$ |
|----------------------|-----------------------|--------|-----------|----------|----------|----------|----------|
| 0                    | 212                   | 109.84 | 82.78     | 32.23    | 52.81    | 72.58    | 132.78   |
| 12                   | 1419                  | 102.34 | 74.10     | 29.35    | 49.79    | 63.47    | 111.33   |
| 24                   | 3179                  | 100.22 | 74.00     | 28.11    | 52.81    | 63.47    | 111.33   |
| 36                   | 1959                  | 95.43  | 75.14     | 25.07    | 52.81    | 65.86    | 108.51   |

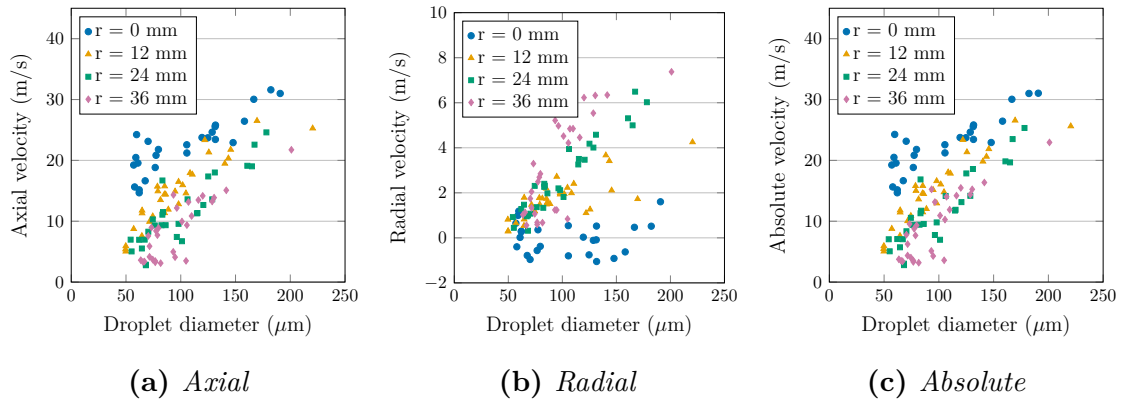
The lower total number of detected droplets at the elevated temperature may possibly be explained by partial evaporation of UWS before imaging. The corresponding histograms for the tabulated values are shown in Figure 4.9. Once again, of the three fitted distributions, the log-normal distribution described the histograms best, whereas the Weibull distribution gave the poorest fit.

## 4. Results and Discussion



**Figure 4.9:** Droplet size distributions for injector #1 for varying radial positions at  $z = 75 \text{ mm}$ ,  $1.67 \text{ g/s}$ , and  $40^\circ\text{C}$ , 3 to 100 ms after SOI.

Comparing the estimated droplet velocity for room temperature and  $40^\circ\text{C}$  UWS injection temperature, no noticeable difference was observed. The axial velocity remained in the range 5-30 m/s as shown in Figure 4.10.



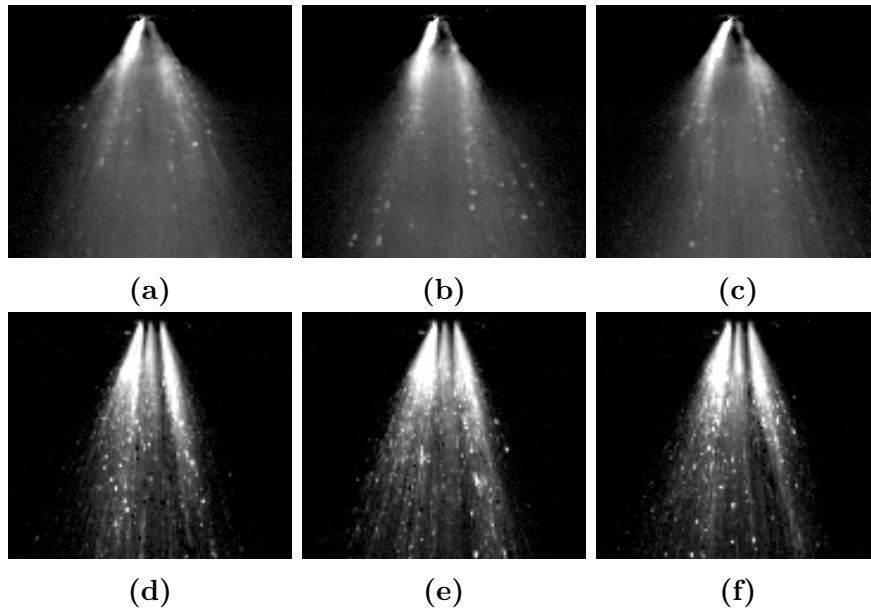
**Figure 4.10:** Estimated axial (a), radial (b) and absolute (c) velocities at  $z = 75 \text{ mm}$  and injection temperature of  $40^\circ\text{C}$  at different radial positions.

Initially, an injection temperature of  $50^\circ\text{C}$  and higher was planned to be used.

However, when testing 50 °C, it was noted that the system failed to inject UWS. It was later found that this was a malfunction from the injection system and was known to the suppliers. Nevertheless, it meant that higher temperatures than 40 °C could not be tested at the time conducting this project.

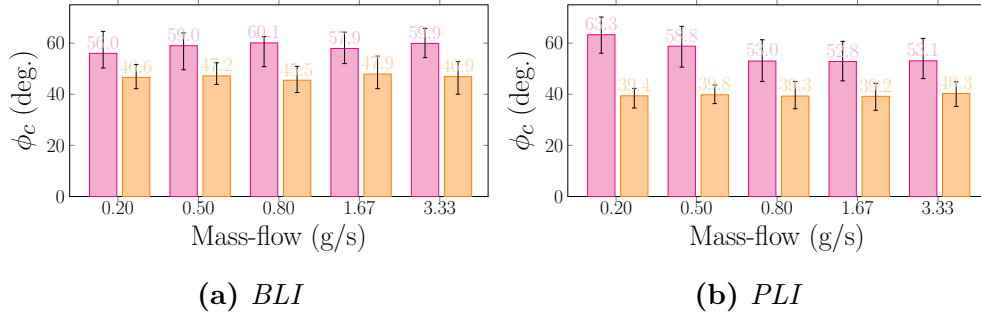
## 4.4 Effect of Injector Type

The PLI measurements made it possible to observe a cross-section of the spray, which clearly showed that injector #1 produced a hollow-cone spray immediately downstream of the nozzle. This can be seen in Figure 4.11, which illustrates the upper part of a developed spray for a UWS mass-flow rate of 0.20 g/s. The outer part of the spray, especially the early stage, appears brighter, indicating a higher local liquid concentration. The swirling nature of injector #1 can also be observed, since the thickness of the white region varies. Injector #2, in contrast, has three pairs of holes, producing three subsprays that are initially separated but converge farther downstream. This can be seen in Figure 4.11d-f where dark lines appear in the upper part of the spray. The lower intensity in the middle region is expected, since only one plane of the spray is analysed and that plane does not intersect each subspray equally.



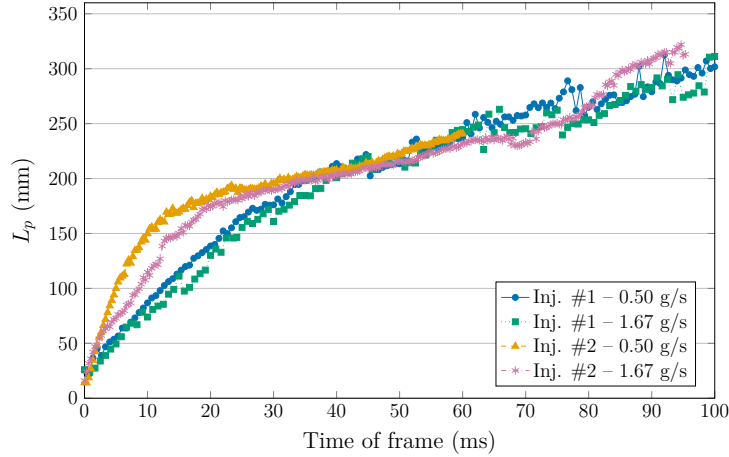
**Figure 4.11:** Three frames with PLI, 500 ms apart of the upper part of a developed spray at a mass-flow rate of 0.20 g/s for injector #1 (a-c) and injector #2 (d-f).

From Figure 4.11, it can also be seen that injector #2 produced a smaller spray cone angle. This was true for all tested UWS mass-flow rates and was observed with both BLI and PLI as shown in Figure 4.12. Since the injector geometry was the main parameter that differed between the two cases, it is likely that this difference in internal geometry caused the observed difference in spray cone angle.



**Figure 4.12:** Spray cone angles for injector #1 and injector #2 measured with BLI (a) and PLI (b). The black bars indicate the minimum and maximum values.

The differences in penetration length for UWS mass-flow rates of 0.50 g/s and 1.67 g/s for the two injectors are shown in Figure 4.13. One noticeable issue is the injection duration at 0.5 g/s for injector #2, which occurred because the injection frequency was mistakenly set to 2 Hz instead of 1 Hz. However, the overall shape of the penetration length curve is not expected to change, since the frequency primarily controls the timing and duration of the injection. Another difference is the rate at which the penetration length increased. Injector #1 required approximately twice as much time as injector #2 to reach a comparable penetration length. Finally, the final penetration length for injector #2 was slightly greater, although it did not show as clear a plateau as injector #1. Since the injection pressure and the mass-flow rates were the same for both injectors, it is reasonable to conclude that the internal geometry of the injectors was a major factor affecting how quickly the penetration length developed.



**Figure 4.13:** Penetration length for the two injectors at UWS mass-flows of 0.50 and 1.67 g/s.

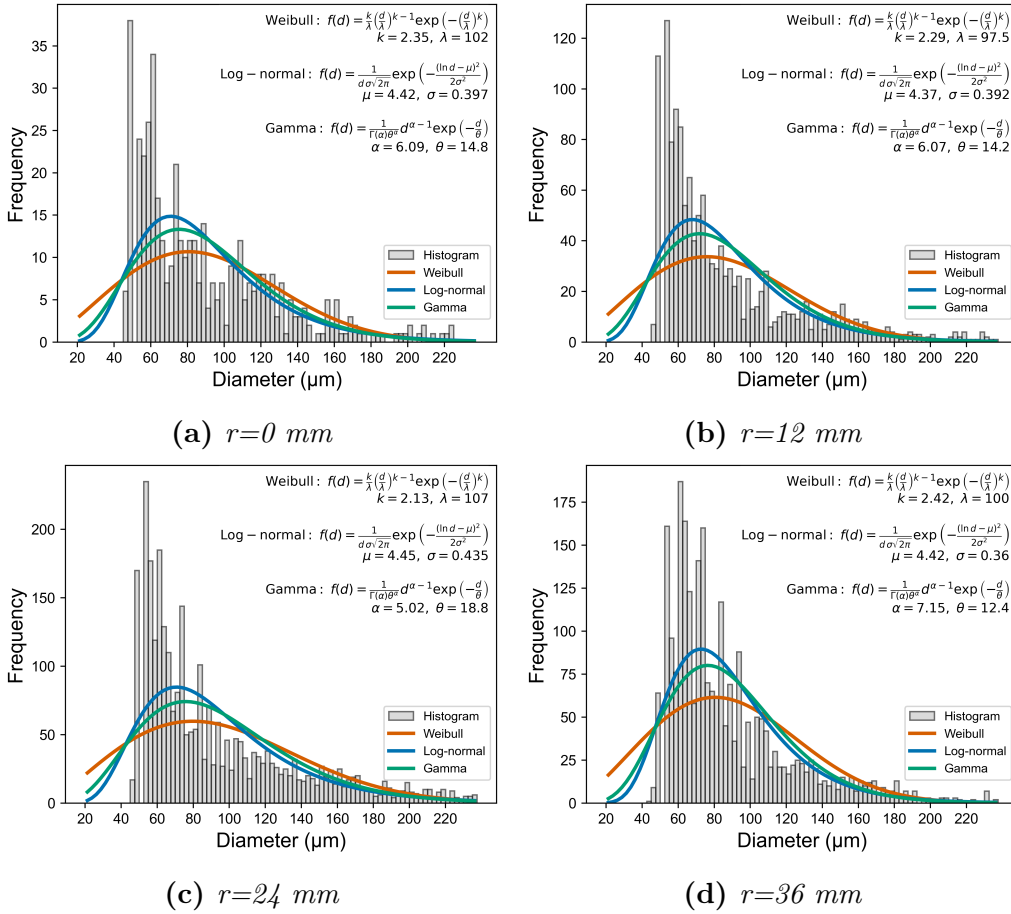
The droplet size metrics also differed between the injectors, as shown in Table 4.5, which presents the droplet size results for injector #2. When Welch's t-test was performed, no significant difference was observed at radial position 0 mm, whereas injector #2 showed significantly larger mean diameters than injector #1 at radial positions 12 mm, 24 mm, and 36 mm. Figure 4.14 presents the frequency-based droplet-size histograms together with fitted Weibull, log-normal, and gamma

## 4. Results and Discussion

distributions. These results indicate that the Weibull distribution provided the poorest fit, whereas the log-normal and gamma distributions performed better.

**Table 4.5:** Droplet size metrics ( $\mu\text{m}$ ) for injector #2 at  $z = 75\text{ mm}$ ,  $1.67\text{ g/s}$ , and room temperature at different radial positions, 3 to 100 ms after SOI.

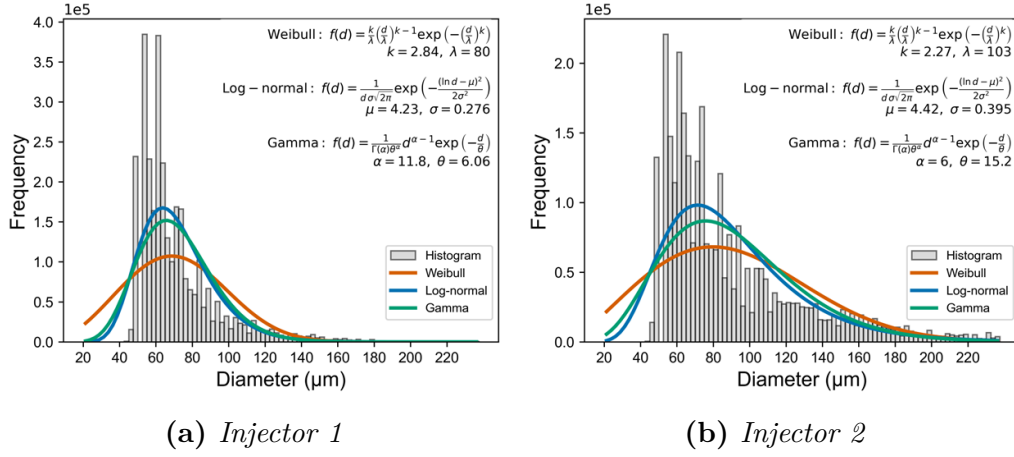
| Radial Position (mm) | $N_{\text{droplets}}$ | SMD    | $\bar{d}$ | $\sigma$ | $d_{10}$ | $d_{50}$ | $d_{90}$ |
|----------------------|-----------------------|--------|-----------|----------|----------|----------|----------|
| 0                    | 456                   | 130.46 | 90.23     | 40.44    | 52.81    | 77.73    | 143.01   |
| 12                   | 1396                  | 127.08 | 86.07     | 39.62    | 52.81    | 70.41    | 147.27   |
| 24                   | 2908                  | 146.84 | 94.62     | 47.52    | 52.81    | 76.73    | 165.13   |
| 36                   | 2527                  | 127.05 | 88.88     | 37.95    | 55.65    | 76.73    | 141.26   |



**Figure 4.14:** Droplet size distributions for injector #2 at  $z = 75\text{ mm}$  and  $1.67\text{ g/s}$ , 3 to 100 ms after SOI.

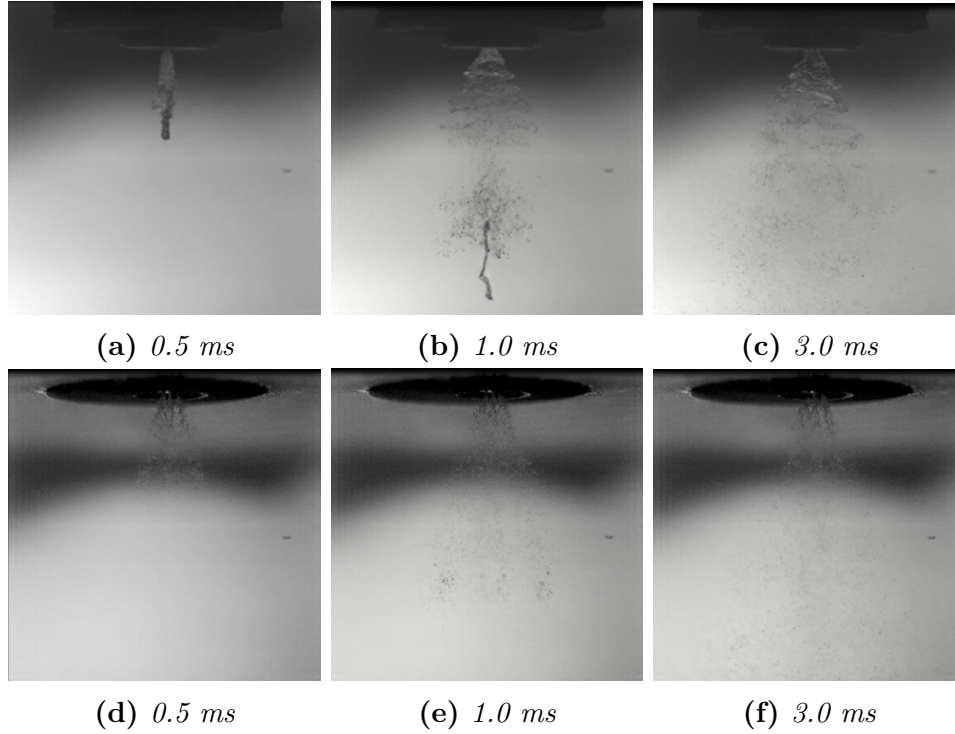
Using the scaling factors to estimate the entire cut-through at  $z = 75\text{ mm}$  for both injectors, as shown in Figure 4.15, also indicated that injector 1 had both a lower SMD and arithmetic mean droplet diameter. For injector #1,  $\text{SMD}=92.45\text{ }\mu\text{m}$ ,  $\bar{d} = 71.71\text{ }\mu\text{m}$ , and  $\sigma = 24.26\text{ }\mu\text{m}$ . For injector #2,  $\text{SMD}=135.72\text{ }\mu\text{m}$ ,  $\bar{d} = 90.87\text{ }\mu\text{m}$ , and  $\sigma = 42.23\text{ }\mu\text{m}$ . The fitted distributions, mainly log-normal and gamma, described the histograms better compared to the individual radial positions.

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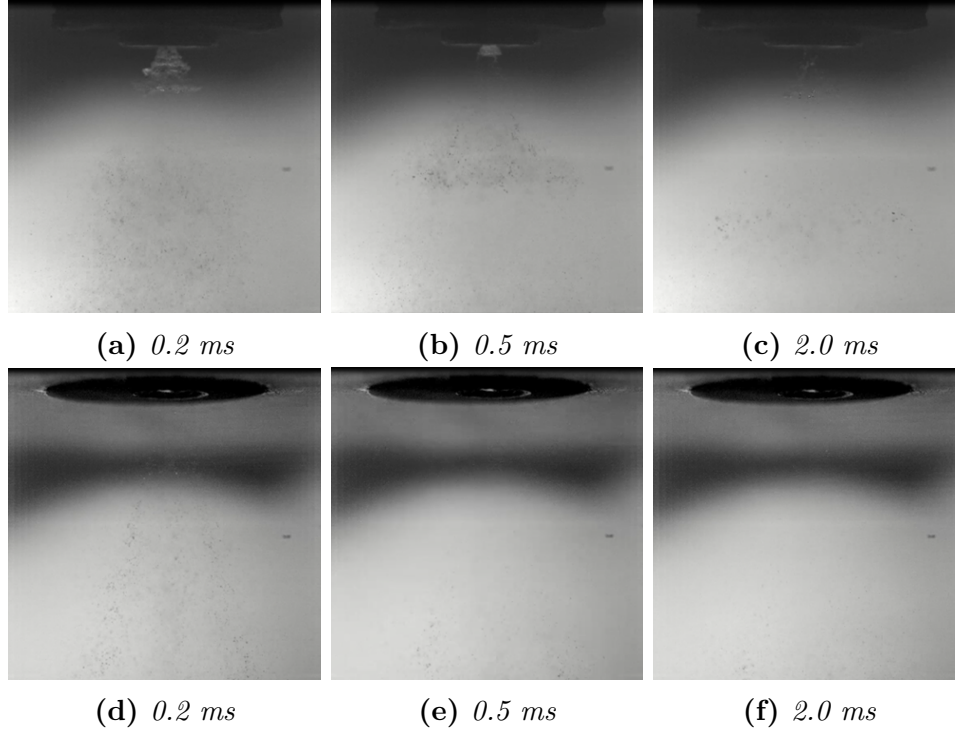
**Figure 4.15:** Droplet size distributions using scaling factors at  $z = 75$  mm.

The time required to reach a developed spray, as well as the spray-closing behaviour, differed slightly between the injectors. Figure 4.16 illustrates the opening sequence, where it can be seen that the morphology during the transient phase differed significantly. Injector #1 more closely followed the spray-development stages illustrated in Figure 2.3 from the theory chapter with a distorted pencil and onion or tulip stage being identifiable. Injector #2 did not undergo equally distinct morphological changes, but instead mainly retained and extended its original shape.



**Figure 4.16:** MBLI images 0.5, 1.0, and 3.0 ms after SOI for injector #1 (a-c) and injector #2 (d-f).

The closing behaviour of the injectors also differed, both in morphology and duration. Injector #1 closed through three pulsations before shutting off completely, which took approximately 2 ms. Some of these pulses can be seen in Figure 4.17. Injector #2, on the other hand, shut off almost immediately which took approximately 0.5 ms. As a result, no spray is visible at 2 ms for injector #2 in Figure 4.17.



**Figure 4.17:** MBLI images 0.2, 0.5, and 2.0 ms after closing injector #1 (a-c) and injector #2 (d-f).

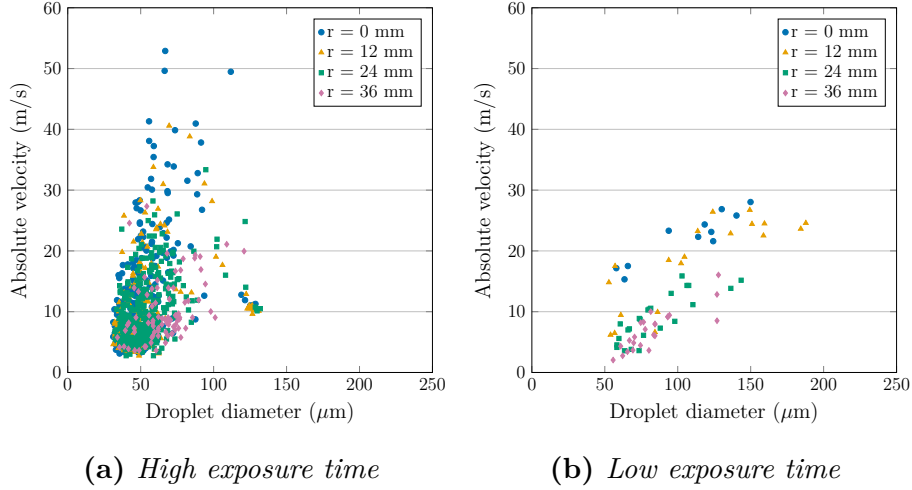
The droplet morphology varied slightly over time for both injectors. It was observed that the circularity varied even for small droplets. This may be because the smaller droplets occupied very few pixels with the available macro lens, which would affect the circularity calculation. A macro lens with greater magnification would therefore likely have been preferable, although this would also have reduced the number of droplets captured in each image. Circularity alone does not fully describe whether a shape is circular, and eccentricity is therefore also important to consider. The lowest eccentricities were observed for the smallest droplets, which is consistent with the expectation that smaller droplets are more nearly spherical.

In summary, the injector type had a clear effect on both macroscopic and microscopic spray characteristics. Injector #1 produced a greater spray cone angle. Regarding the microscopic properties, the droplets from injector #1 were generally smaller and the spray exhibited a more hollow character than that of injector #2.



## 4.5 Evaluation of Velocity Measurement Methods

Velocity was estimated using two different MBLI-based techniques. One major difference between them was the computation time. For the technique using longer exposure time, no manual processing was required, which made it possible to obtain many more data points within a reasonable time, as shown in Figure 4.18. The techniques using longer exposure time also yielded some absolute velocity values that were higher than those obtained with the shorter exposure technique. It was also more difficult to draw conclusions about the droplet size-velocity relationship from the longer exposure time measurements. However, the droplet size estimation is likely more accurate when having shorter exposure time, since the droplets are more clearly defined. This is not the case for longer exposure time, where the droplets appear as streaks rather than distinct particles. It is also noteworthy that the smallest detected droplet diameter differed between the two techniques.



**Figure 4.18:** Absolute velocity of droplets using a longer exposure time (a) and shorter exposure time (b).

Based on Figure 4.2, an apparent spray-front velocity can also be estimated. At  $t = 10$  ms and  $t = 20$  ms, the corresponding average velocities are approximately 7.5 and 7.0 m/s, respectively. These values are of the same order of magnitude as the droplet velocities obtained from the two MBLI techniques, although they lie closer to the lower end of the measured droplet-velocity range.

# 5

## Conclusions

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During the project, a simple in-house setup for estimating spray cone angle, penetration length, and droplet size was successfully constructed, together with Python scripts for evaluating the results. The setup provides a practical basis for future injector testing at Volvo Penta.

The spray cone angle was estimated to be approximately  $15^\circ$  lower for injector #2 than for injector #1, which represents a significant difference. Despite this, the spray width was greater for injector #2. Depending on the available depth of the system in which the injectors are installed, the risk of wall impingement may therefore be similar for the two injectors. Regarding the penetration length, no major difference was observed overall. However, injector #2 showed a faster increase in penetration length during the first 20 ms after SOI.

For injector #1, more droplets were detected farther from the centreline, which supports the interpretation that the swirl injector produced a hollow cone spray. At the same time, both axial velocity and droplet size decreased with increasing radial position. Although this may appear counter-intuitive, since no liquid is injected directly through the spray centre, it is consistent with the observed hollow-cone structure and the downstream redistribution of droplets.

Comparing the two injectors, injector #2 produced larger droplets than injector #1 with a statistical significance at  $p \leq 0.05$ . Injector #1 had more radial variation in droplet size than injector #2 showed. For injector #1, the increase in UWS temperature produced a statistically significant difference in droplet size only at the two outermost radial positions, at a significance level of  $p \leq 0.05$ . No significant difference was observed at the two positions closest to the centreline.

Velocity measurements using MBLI proved to be challenging, especially at the central positions, with the available equipment. Nevertheless, the measured velocity range was of the correct order of magnitude for the relatively simple techniques that were used. More advanced techniques, such as laser Doppler anemometry or phase Doppler anemometry would be beneficial for further validation.

# 6

## Future Work

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Several limitations were necessary because of time constraints and limited equipment availability. In this project, only quiescent ambient air was considered, which provided a good understanding of how the injector behaves under simplified conditions. However, the intended application rarely involves quiescent ambient air, and it would therefore be highly relevant to perform measurements in flowing exhaust gas at elevated temperatures.

Since the current setup appeared to impose a lower detection limit on droplet size, a complementary technique such as laser Doppler anemometry or phase Doppler anemometry would provide useful additional data. Replacing the lens with one of higher magnification would also be of interest in order to determine whether the current optical setup limits the detection of smaller droplets. Another benefit of using a technique such as laser Doppler anemometry or phase Doppler anemometry is that more detailed spatially resolved information about the spray can be obtained.

The techniques used in this project were considered successful and yielded relevant data. It should therefore be possible to test other injectors in-house in future work. The experimental results could also be compared with existing CFD models, using the measured data as input and for simulation validation.

# References

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- [1] International Energy Agency, *Energy efficiency 2025*, Licence: CC BY 4.0, Paris, 2025. [Online]. Available: <https://www.iea.org/reports/energy-efficiency-2025/transport>.
- [2] Eurostat. “Final energy consumption in transport — detailed statistics.” Section: Water transport. Statistics Explained article. Accessed: 2026-01-22. [Online]. Available: [https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Final\\_energy\\_consumption\\_in\\_transport\\_-\\_detailed\\_statistics#Water\\_transport](https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Final_energy_consumption_in_transport_-_detailed_statistics#Water_transport).
- [3] Swedish Environmental Protection Agency. “Nitrogen oxides.” Utsläpp i siffror (Emissions in figures). Accessed: 2026-01-22. [Online]. Available: <https://utslappisiffror.naturvardsverket.se/en/Substances/Other-gases/Nitrogen-oxides/>.
- [4] L. Han et al., “Selective catalytic reduction of NOX with NH3 by using novel catalysts: State of the art and future prospects,” *Chemical Reviews*, vol. 119, no. 19, pp. 10916–10976, 2019.
- [5] E. Kristensson, “Structured laser illumination planar imaging slipi applications for spray diagnostics,” Doctoral Thesis (compilation), Combustion Physics, 2012, ISBN: 978-91-7473-269-6.
- [6] L. Ström, H. Ström, A. Darnell, P.-A. Carlsson, M. Skoglundh, and H. Härelind, “Quantification of Urea-spray Non-uniformity Effects on the H2-assisted NO Reduction and NH3 Slip over an Ag/Al2O3 Catalyst,” *Energy Procedia*, vol. 75, pp. 2317–2322, 2015.
- [7] S. Sebelius, T. T. Le, L. J. Pettersson, and H. Lind, “Identification of urea decomposition from an SCR perspective; A combination of experimental work and molecular modeling,” *Chemical Engineering Journal*, vol. 231, pp. 220–226, 2013.
- [8] S. Halonen, T. Kangas, M. Haataja, et al., “Urea-Water-Solution Properties: Density, Viscosity, and Surface Tension in an Under-Saturated Solution,” *Emission Control Science and Technology*, vol. 3, pp. 161–170, 2017.
- [9] W. Brack et al., “Kinetic modeling of urea decomposition based on systematic thermogravimetric analyses of urea and its most important by-products,” *Chemical Engineering Science*, vol. 106, pp. 1–8, 2014.

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- [10] K. Sun et al., “Study on Urea Crystallization Risk Assessment and Influencing Factors in After-Treatment System of Diesel Engines,” *Applied Sciences*, vol. 14, no. 2, 2024.
- [11] J. Schmid, I. Zarikos, A. Terzis, N. Roth, and B. Weigand, “Crystallization of urea from an evaporative aqueous solution sessile droplet at sub-boiling temperatures and surfaces with different wettability,” *Experimental Thermal and Fluid Science*, vol. 91, pp. 80–88, 2018.
- [12] H. Dong, S. Shuai, and J. Wang, “Effect of Urea Thermal Decomposition on Diesel NOx-SCR Aftertreatment Systems,” Jun. 2008.
- [13] G. Zheng, T. Gardner, A. Motrba, and M. Golin, “Development of urea scr systems for large diesel engines,” SAE Technical Paper 2011-01-2204, Tech. Rep., 2011.
- [14] A. H. Lefebvre and V. G. McDonell, *Atomization and Sprays*. CRC Press, 2017.
- [15] “Fundamentals of mixture formation in engines,” in *Mixture Formation in Internal Combustion Engine*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2006, pp. 5–46, ISBN: 978-3-540-30836-2.
- [16] P. Senthilkumar and T. Anand, “Examination of urea water solution spray characteristics in hot cross flow,” *Experimental Thermal and Fluid Science*, vol. 172, p. 111635, 2026.
- [17] N. Ashgriz, *Handbook of Atomization and Sprays*. Springer, 2011.
- [18] B. E. Rapp, “Chapter 9 - fluids,” in *Microfluidics: Modelling, Mechanics and Mathematics*, ser. Micro and Nano Technologies, B. E. Rapp, Ed., Oxford: Elsevier, 2017, pp. 243–263, ISBN: 978-1-4557-3141-1.
- [19] O. Taskiran and M. Ergeneman, “Experimental Study on Diesel Spray Characteristics and Autoignition Process,” *Journal of Combustion*, vol. 2011, Mar. 2011.
- [20] O. Moussa, A. Mattsson, M. Andersson, J. Sjöblom, and P. Dahlander, “Characterization of adblue sprays macroscopic properties using optical methods under realistic driving conditions,” 2021.
- [21] F. Huzjan, F. Jurić, S. Lončarić, and M. Vujanović, “Deep Learning-based Image Analysis Method for Estimation of Macroscopic Spray Parameters,” *Neural Computing and Applications*, vol. 35, no. 13, pp. 9535–9548, 2023.
- [22] R. Klein-Douwel, P. Frijters, L. Somers, W. de Boer, and R. Baert, “Macroscopic diesel fuel spray shadowgraphy using high speed digital imaging in a high pressure cell,” *Fuel*, vol. 86, no. 12, pp. 1994–2007, 2007.
- [23] *Sauter mean diameter*, Feb. 2011. DOI: 10.1615/AtoZ.s.sauter\_mean\_diameter.
- [24] S. Kooij, R. Sijs, M. M. Denn, E. Villiermaux, and D. Bonn, “What Determines the Drop Size in Sprays?” *Phys. Rev. X*, vol. 8, p. 031019, 3 Jul. 2018.
- [25] E. Cerruto, G. Manetto, R. Papa, and D. Longo, “Modelling Spray Pressure Effects on Droplet Size Distribution from Agricultural Nozzles,” *Applied Sciences*, vol. 11, no. 19, 2021, ISSN: 2076-3417.

- [26] J. Oh and K. Lee, “Spray characteristics of a urea solution injector and optimal mixer location to improve droplet uniformity and NO<sub>x</sub> conversion efficiency for selective catalytic reduction,” *Fuel*, vol. 119, pp. 90–97, 2014.
- [27] J. Oh, K. Kim, and K. Lee, “Spray characteristics of four-hole injectors used for a hydrocarbon lean nitrogen oxide catalyst system in a diesel engine,” *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 226, no. 8, pp. 1073–1087, 2012.
- [28] R. Castrejón-García, J. Castrejón-Pita, G. Martin, and I. Hutchings, “The shadowgraph imaging technique and its modern application to fluid jets and drops,” *Revista Mexicana de Física*, 2011.
- [29] B. P. Husted, P. Petersson, I. Lund, and G. Holmstedt, “Comparison of PIV and PDA droplet velocity measurement techniques on two high-pressure water mist nozzles,” *Fire Safety Journal*, vol. 44, no. 8, pp. 1030–1045, 2009.
- [30] D. Nuyttens, M. Schamphelre, P. Verboven, E. Brusselman, and D. Dekeyser, “Droplet Size and Velocity Characteristics of Agricultural Sprays,” *Transactions of the ASABE*, vol. 52, pp. 1471–1480, Sep. 2009.
- [31] O. Moussa, A. Mattsson, M. Andersson, J. Sjöblom, and P. Dahlander, “Urea droplets size distribution measurement using shadowgraphy imaging,” 2021.
- [32] G. B. Thomas and R. L. Finney, *Calculus and Analytic Geometry*, 5th ed. Addison-Wesley, 1979, ISBN: 0-201-07540-7.